ENGINEERING CASE LIBRARY

ECL 189A

LASER HARDWARE (A)

Breadboard Design

April 20, 1970, Fred Moreno was asked to attend a meeting on the 23rd of April about the thermal and mechanical aspects of the Laser Communications Experiment (LCE). The experiment was for the Applications Technology Satellite (ATS) (Model F) to be launched by NASA in November 1972. At the meeting there would be representatives from NASA, Aerojet General Corporation, the prime contractor for the Laser Communications Experiment and Sylvania's Electro-Optics Organization (E.O.O.), subcontractor to Aerojet for the lasers. Fred was a mechanical engineer working for Sylvania Electronic Systems. Although his group was not a part of E.O.O., Fred had been asked to assist in analyzing some heat transfer problems for them. He was told that his level of effort on the ATS would be "moderate", about twenty hours per week. This suited Fred for he had another project which was tapering off but which still demanded about half his time. Consequently the ATS would dovetail nicely into his schedule.

 Written by Fred Moreno and edited by G. Kardos. Published with support from the National Science Foundation.

Fred Moreno was a twenty-four year old mechanical engineering graduate of the University of California, Santa Barbara. His early interest in auto and go-kart racing fired his interest in engineering although it sometimes made it difficult for him to concentrate on his academic pursuits. Fred had considered taking forestry or biology at the university but rejected them because he felt a need to work with hardware.

Since joining Sylvania, Mountain View, in 1968, after graduation, he worked on a variety of classified electronic systems and the vehicles to carry them. He has since developed a broad interest in electronics but not sufficient to regret not being an electrical engineer. While working at Sylvania he was studying for his Master's degree in Mechanical Engineering at Stanford University.

The Laser Communications Experiment (LCE) which Fred was asked to work on was to be a laser system which would be used to determine if lasers were a more cost effective system for deep space communications than other comparable systems. Lasers appeared to offer an excellent means of communicating between satellites and between satellite and ground because the narrow beam transmission affords a high degree of privacy. It also allows more of the transmitted power to be delivered to the receiver, thus requiring less total power. The final criteria for comparison between the laser system and conventional microwave systems would be the cost per bit of information transferred. The microwave system transmitter costs less than a laser transmitter, but the solar panels and power supplies necessary to drive it, with the large antennas needed for transmission, weigh more than a comparable laser system. The cost in terms of fuel and booster size would consequently be greater. Sylvania Electro-Optics Organization was to supply the laser for a system to establish feasibility and cost effectiveness.

When Fred was assigned to the project he knew little about the lasers. In the following narrative, Fred related how he learned about laser communications and tackled some of the problems related to designing and building a working laser system.

> *I knew little about ATS until a few days before the meeting. I knew by talking to Walt Anderson, the chief technical man on the project, that the system consisted of three lasers plus associated optics for handling the laser beams, and some electronics. Three lasers were to be used: a transmitting laser, a local oscillator laser (part of the receiving system), and a back-up laser to be used should either of the first two fail. All lasers were of the CO_2 gas type, and the largest of*

the three generated about one watt of optical output at 10.6 microns wavelength. The transmitting tube contained a modulator used to impose information onto the laser output by frequency modulation. The system was to be capable of communicating with ground from the ATS vehicle parked in stationary orbit 22,000 miles from Earth. Minimum system weight, minimum power consumption, and maximum reliability were foremost considerations in design.

I told Walt that what I knew about lasers was limited to what I had picked up in Scientific American magazine. I knew that the CO_2 laser operated by passing an electric current through a low pressure gas discharge (like a neon sign), and that this caused a population inversion of excited levels of molecules. Excited molecules, in decaying to lower energy levels emit photons of a given frequency. By putting mirrors on either end of gas discharge, one could reflect these photons back through the gas. When such a photon interacts with an excited molecule the molecule voluntarily dumps its photon and comes down to the lower energy level. Two photons then emerge to interact with two more molecules, and the process continues. A portion of the optical power that circulates between the mirrors is bled out by making one of the mirrors partially transparent. The resulting output beam is well collimated, and if the laser is properly controlled, the output is monochromatic (single frequency) and coherent (in phase), and can be used to carry information. This much I knew, but that was the limit of my knowledge. I told Walt I had no idea of the size and complexity of the equipment, or of what the equipment he was talking about looked like. He assured me that that was no problem, that I would learn it quickly.*

We walked to one of the labs where a laser similar to the one to be built for ATS was operating. What I saw was a laser tube, about the size and shape of a beer can, with "Brewster" angle windows out either end, and two end cavity mirrors facing the windows. The cavity, I learned, was the space between the mirrors in which the laser power circulated. For the LCE the transmitter cavity would contain a tube and a modulator.

**For those interested in learning about lasers in a general way, I recommend Lasers and Light, a collection of articles from Scientific American through 1968. (In paperback, $5.95)*

Walt gave me a copy of the proposal which Sylvania had submitted during competition some months earlier, and told me to go home and study it so I would know what was going on during the meeting on April 23. That evening and the next I did just that, spending about 15 hours reading what I could understand in the proposal, and writing off the rest as unintelligible.

It was in this intensive study period that I began to learn about ATS and its lasers. Here I found a picture of what the transmitter was to look like (Exhibit A-1) with the modulator installed. Brewster angle windows were used because the laser radiation would be polarized, and polarized light passes through Brewster angle windows without reflection losses. These windows would be of gallium arsenide, one of the few materials transparent to infrared radiation. The modulator was a crystal of gallium arsenide arranged at Brewster's angle. Two electrodes would be soldered to either side of the crystal. When a voltage is applied, the net effect is to change the laser frequency slightly. Information is thus imposed on the laser output by varying its frequency about some center frequency.

I would be concerned with thermal problems associated with the laser tube and the modulator, so I studied these areas most closely. I learned that the tube likes to run as cool as possible. The power input to the electric discharge would be about twenty watts, with one watt emerging as useable output. The rest is heat and would have to be conducted away to the spacecraft structure. The modulator likes to run at constant temperature. The electrical effect imposed by the electrodes is very small, and can be washed out if the crystal temperature is not held to within ±0.5°C. A heater having a maximum power of two watts was planned, with a temperature control circuit to hold the modulator temperature constant. The proposal specified a modulator temperature of 50°C for a spacecraft environment (vacuum) of -5°C. to ±40°C.

The meeting of 23 April was not much help to me. My quick study made me familiar with the general aspects of the system: theory of operation, size, weight, general configuration, power consumption, and temperature ranges. The main concern of the meeting was to iron out details of design and operation. Not being familiar with the details, I was left out in the cold, and I tried to stay as inconspicuous as possible while trying to learn something.

One thing I did understand was that Sylvania was to design and construct a breadboard of the system (a crude operating system to demonstrate feasibility) by 20 June, less than eight weeks away. As an extra inducement to meet schedule, the NASA contract provided an incentive of several thousand dollars if we made delivery on time. Inasmuch as the system existed at the time only as sketches and ideas, with no drawings or detail design, I found myself emerging from the meeting more than a little disturbed.

Later that day I caught Walt Anderson in his office, and I asked him why we had such a difficult schedule, and what the schedule for the rest of the job would be. It seems that originally another contractor had teamed with Aerojet for the job with that contractor to produce the lasers and associated equipment. That contractor worked for six months, but was unable to build a laser that did the job satisfactorily. As a result, they missed several successive critical schedule dates. Meanwhile, Sylvania had independently built an unrefined but effective laser that met most of the specifications. NASA was made aware of this, and several months later, they terminated the contract with the original laser contractor, and opened a new contract with Sylvania, but only on the condition that Sylvania would catch up the lost time and thus make the November 1972 launch date schedule. Sylvania agreed.

The job itself was to be divided into three phases. The first, a breadboard to demonstrate the feasibility of the approach. Then would follow the Functional Test Model (FTM) which was to be our best attempt at flight equipment. The FTM would be given extensive testing. Based upon the results of the FTM, two flight hardware systems would be constructed in the third phase, and one of these would be launched in November 1972.

Walt gave me a copy of the schedule for the modulator, the equipment that I was to concentrate my efforts on. The schedule (Exhibit A-2) showed time allotments for design of the gallium arsenide crystal including attachment of the electrodes, design of the clamp to hold the crystal, and design of the housing to hold the crystal-clamp assembly. Fabrication time for each of the above was included.

Finally Walt introduced me to John Sullivan, the optical engineer with overall responsibility for the modulator. When I told John that I knew nothing about modulators except what I had read in the proposal, he

promptly gave me an excellent cram course on the theory of operation, problems to be solved, and the design as he presently envisioned it. He was primarily concerned about the temperature stability of the crystal. Here I should point out that my best information about lasers came from the engineers on the program. These people lived lasers and laser systems, and were able to distill out bits of information to help me understand the various aspects of laser operation. They were always patient and more than willing to answer the dumbest questions I could think of. I have to credit the optical engineers and physicists on the program for teaching me most of what I know about lasers.

I began by immediately calculating the expected temperature gradients in the modulator based upon the power dissipation figures and preliminary sketches John had given me (Exhibit A-3). As an example, I calculated the expected temperature gradient in the gallium arsenide due to energy absorbed from the laser beam. I modeled the crystal as a slab 0.3cm thick with uniform internal heating. The resulting temperature profile is parabolic, and the maximum temperature difference between the warmest and coolest part of the crystal is 0.007°F.

The crystal was to be clamped between two pieces of boron nitride. Boron nitride was selected because it has good thermal conductivity, to carry heat from the crystal to the modulator case, a low dielectric constant to reduce the stray electrical capacitance in the modulator thus reducing the power required to drive it and because it has low density to reduce weight. Few people were familiar with the material, so I checked through catalogues to find the pertinent data. Boron nitride is a refractory material made by pressing powder into a solid under heat and pressure. The material is anisotropic, with most of its properties varying by a factor of about two depending on direction. I went back to some heat transfer textbooks to see what analytical tools were available for anisotropic materials. You have to go all the way back to the basic equations and treat thermal conductivity as a variable rather than a constant, and the resultant analysis becomes moderately hairy and very time consuming, particularly if you have to learn the new theory first. In view of the time limitations I chose to ignore the effect, and take an average*

**See, for example, Ozisik, Boundary Value Problems in Heat Conduction, International Textbook Co., 1968, Chapter 10.*

value together with an educated guess of what variations might arise due to my simplifications. I calculated a maximum temperature gradient at the junction of the crystal and the boron nitride of 3.65°F./in., and at the interface of the boron nitride and aluminum housing of 1.14°F. per inch (using a simplified one-dimensional model). My guess was that the effects would be small, and later testing showed that this was the case.

My next concern was to calculate the power requirements to maintain the modulator temperature as the spacecraft ambient varied. The problem as outlined to me was simple. The modulator temperature was to be kept constant at 50°C. by varying the heater power as the ambient temperature of the spacecraft varied over a range of -5°C. to 40°C. The maximum allowable heater power would be 2 watts. This comprised all the information available about the problem.

I started by writing governing equations involving the modulator temperature, the ambient temperature range, and the power dissipations in the crystal and heater. In first cut form, the equations are very simple:

$$Q_{crystal\ dissipation} = K^*(T_{mod} - T_{upper\ ambient})$$

$$Q_{heater} = K^*(T_{mod} - T_{lower\ ambient})$$

The first equation expressed the fact that when the ambient temperature is at highest value, the crystal power dissipation alone should keep the modulator temperature at its appropriate value. The second equation expressed the fact that when the ambient temperature is at its lowest value, the heater alone should keep the modulator temperature where it belongs. (This is because the modulator has to stay at a fixed temperature when the laser is not operating, and thus there is no crystal dissipation.)

As I recall I began calculating using the given temperature of 50°C., and noticed some inconsistency. I somehow got a gut feeling that the problem was overspecified, that is, there were too many equations for the problem, and the equation

$$T_{mod} = 50°C.$$

was the extra one. I reexamined the governing equations to see what was wrong. In these equations, K is some effective thermal conductance. The ambient temperature range, crystal dissipation, and maximum allowable heater power were fixed (or would be as more information became available), and it was thus only necessary to*

solve for the modulator temperature and the effective thermal conductance. The problem was complicated somewhat in its complete form because some non-linear radiation heat transfer terms had to be included (the above equations are for conductance only), but the result was only slightly different.

The above exercise may seem reasonably straightforward, but it took several days before I could really get my head screwed on right. First, I was busy, and couldn't spend more than a few minutes on the analysis at any given time. Second, the overspecification of the problem (by specifying an arbitrary modulator temperature) was red herring that led me off the right trail for some time. I try to be conscious of perceptual blocks, but I was taken in on this one.

Armed with the above new found knowledge, I proceeded to calculate the effects of varying the parameters of the problem. In particular, the crystal dissipation was a relative unknown because the absorption coefficient of the gallium arsenide was not yet determined. It turns out that the modulator temperature is a strong function of the crystal dissipation, and this concerned me because of differential thermal expansion problems that get nasty as the temperature increases.

My prime tool for the parameter study was a Hewlett Packard programmable calculator. Computers were available, but they were in another building, and I didn't want to waste time debugging a program and waiting for my program to be processed. A timesharing terminal was available, but it had a habit of dumping your program every now and then, and besides I felt the thing was a general nuisance. The calculator was available, it was flexible, and it was fast. As far as I'm concerned the computer approach to this or most of the problems I have faced ends up being costly overkill. I needed answers right away, and I always got them.

Simultaneous with the analysis of the thermal characteristics of the modulator, I worked with several other engineers and a designer on the design of the crystal assembly and the modulator. Because we were working on a breadboard version, and because time was limited, we were somewhat sloppy, and did things we would not otherwise do. As an example, we clamped the crystal between two machined pieces of boron nitride with the clamping pressure produced by six 2-56 screws tapped into one of the boron nitride halves. Boron nitride machines easily enough, but it has the structural characteristics of a hard bar of soap. The threads stripped if you more

than gently snugged the screws in place, but the limited torque was adequate. Too high a clamping force would change the optical characteristics of the gallium arsenide crystal. This brought out a new problem, that of making good thermal contact between the crystal and boron nitride. Any technique we chose to reduce the resistance would need minimum clamping pressure and introduce no thermal stresses when the modulator was brought up to its operating temperature. An approach was worked out after extensive discussion and was based upon the team's past experience (Exhibit A-4). The crystal was ground to final size. Both sides were electroless nickel plated. Monel electrodes were then carefully soldered to the nickel pads using a low temperature indium-gold eutectic solder. Sheet indium gaskets 0.010 inch thick were placed on the back of the electrodes and mated to the boron nitride clamp-halves. The indium is extremely soft at room temperature, being a little like modeling clay, and it thus requires only a gentle pressure to effect a good thermal contact. A lot of luck together with a large portion of tender loving care by the technicians who assembled the hardware resulted in a remarkably successful design.

This thermal contact problem was to raise its head again in the analysis and design of laser tube cooling.

About this time Dan Rodenberger, the lead mechanical engineer of the project, asked me to be responsible for the design and construction of the laser end cavity mirror mounts. He explained the pressing problems of schedule that had to be met with mirror design.

After reviewing what had to be done, I chose to ignore the contact resistance problem temporarily and use silicone grease on the breadboard. In the electronics industry, the thermal contact resistance is usually handled by applying a film of thermally conductive grease to the surfaces, and the result is generally adequate for most uses. However, for use in vacuum, we are concerned with evaporation of substances like silicone grease and some metals because even extremely small evaporation rates could deposit a degrading film on the laser optics.

Because of the heavy workload I was carrying, I was forced to drop one of the courses I was taking at Stanford. Also about this time the program personnel received a pleasant surprise. We had been working evenings and some Saturdays to meet the tight day to day schedule. On May 14 overtime pay was authorized by the program office.

The laser mirror mounts for the breadboard represented a different challenge from the modulator. The breadboard was to show feasibility. It was to do so, when possible, in a manner consistent with the system size, weight, and power specifications. The breadboard modulator was within specification on size and power consumption, but it weighed twice what it was supposed to, primarily due to a thick layer of aluminum around the boron nitride clamps to prevent stray electromagnetic radiation from leaking from the electrodes and into the system electronics. We decided that we would try to make up the weight difference in the mirrors, and thus hold the system overall weight, about eleven pounds within the specification.

The mirror mounts had to hold the mirrors to an angular tolerance of less than a milliradian to prevent misalignment losses. They had to do so through the launch environment which consisted of several minutes of high level random vibration caused by the booster and second stage engines. The mirrors were not temperature compensated, and had to hold position and angle over the whole expected ambient temperature range. The mounts had to be universally adjustable with respect to angle within a range of ±1 degree. All in a package of minimum size and weight.

The mirrors were small, about three eighths of an inch in diameter. They are usually mounted on a triangular metal pad pivoted on one corner, with pitch and yaw angle adjustment screws on the other two. It was obvious that such an assembly would be entirely too large and heavy for us. At this time there was no need for integral adjustment hardware. The laser could be aligned and locked before launching. We thus concentrated our efforts on a compact package that would require some kind of removable adjusting tool.

There never seems to be a clear-cut analytical procedure for this kind of problem such as one might find in a textbook problem. Our approach was to sketch on scraps of paper and backs of envelopes, and discuss it in small groups of two to four people. Whenever we came across something that looked promising, we would lay it out on paper to scale, and see if the new idea was indeed as good as it first seemed. None were, but the layout procedure quickly weeded out the real possibilities, and we kept telling each other to try something new. It's hard to be creative when you are tired, in a hurry, and when somebody asks how you are doing on your schedule every couple of hours. The final approach taken on the breadboard mirrors is shown in Exhibits A-5 and A-6.

The output mirrors through which the laser output passes the mirror were mounted on a stainless steel sphere with a hole through it. The sphere was clamped into a spherical seat by an aluminum piece secured with four screws. (Exhibit A-5) It was adjusted with a tool consisting of a hollow tube, through which the output radiation passed, screwed into the back of the sphere. (Exhibit A-7) The movement of the hollow tube was controlled by extremely fine thread screws mounted on a separate assembly about six inches from the mirror mount. The fine thread allowed small angular changes to be made with ease. A rubber band was used to hold the tube against two of the adjustment screws for pitch and yaw angular changes. The other screws served to hold the tube in place while the mirror ball was clamped.

Space limitations on the non-output mirror required that the screws thread directly into the spherical mirror holder. This was because the non-output mirror was mounted on a pizeoelectric bimorph, a circular wafer about one inch in diameter. The bimorph is the electric equivalent of the bimetallic strip used in thermostats. Application of voltage causes it to bend, and this moves the mirror a small, but controllable distance. By moving the mirror one changes the length of the cavity and thus has control over the centerline frequency of the laser.

The size of the bimorph would have required a ball of excessive size and weight if the output mirror design were used. We thus elected to use only a small hemisphere behind the mirror itself, and secure this in its seat with three mounting screws. (Exhibit A-6). The problem with this arrangement was that tightening of the screws changed the angle of the mirror. There seemed to be no way out of this problem, so I decided to go ahead and make the mount this way, and take hell from the technician who had to adjust the mirrors. I was sure it could be done by a process of trial and error, but I was equally sure it would be difficult and time consuming.

About this time NASA agreed to a new schedule. The program office shuffled the schedule a bit and gave us until 26 June to complete fabrication of hardware, but at cost of a week of testing and assembly.

As the mirror design was being finished, the modulator fabrication was nearing completion, and the machinists were available to fabricate the mirror mounts. We decided to dimension and use the layout drawings we had and to make formal drawings later for the record. The designers and engineers would work closely with machinists, Ed Wolfe and Jack Wiseman, during fabrication to iron out

problems as they arose, and make quick decisions when they were required.

Ed and Jack proved to be very helpful resolving problems that arose, often on an hourly basis. They identified a major oversight on my part, and also proposed the solution. If you look at the construction of the mirror mounts, you can easily see that when the locking screws are loose (as they would be during adjustment) the spheres would tend to fall out of their seats. It is obvious if you study the design for a while, but I managed to miss it, as did everyone else deeply involved in the design phase.

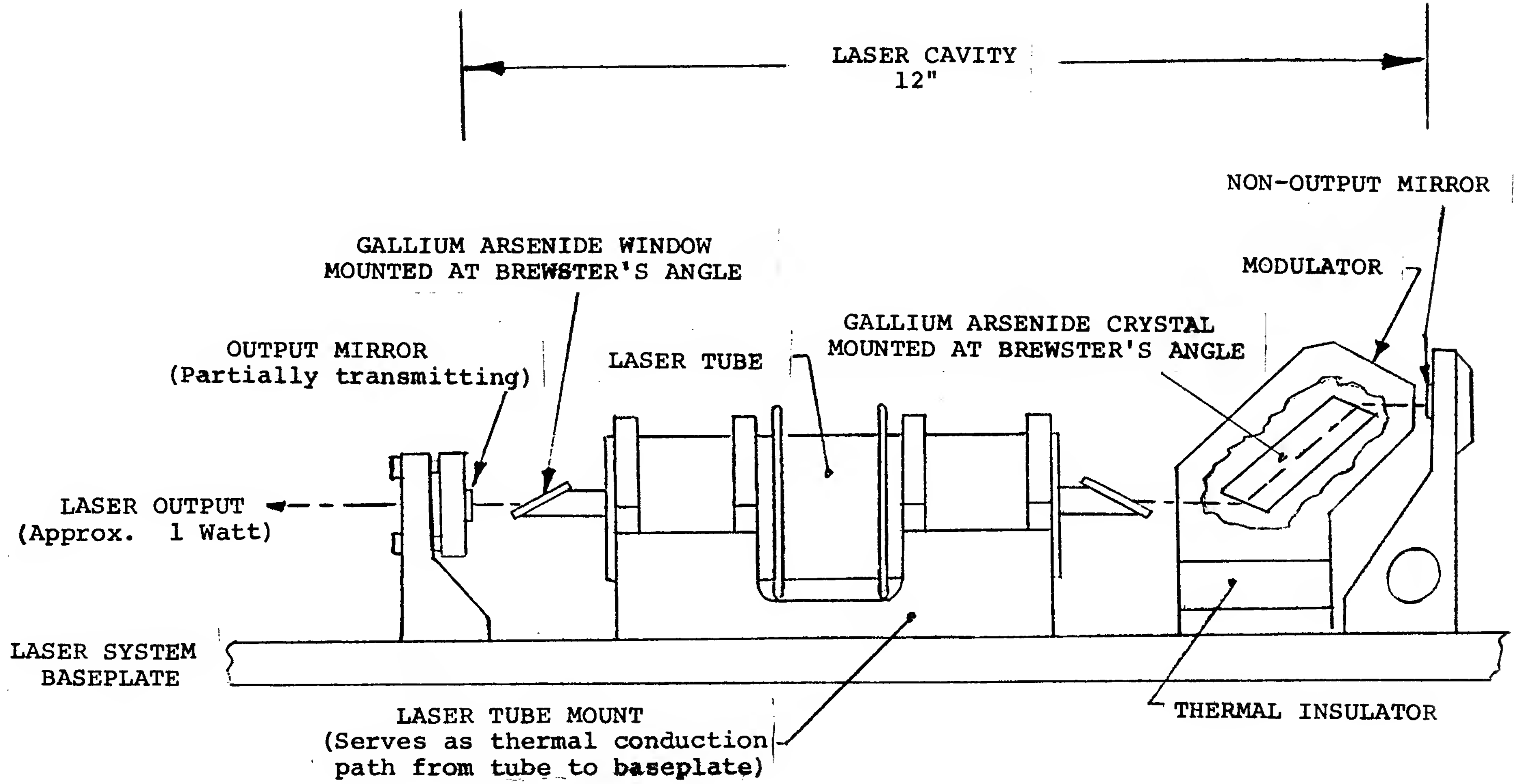
The solution proposed by Jack was to keep the spheres in place using a spring between the mirror mount frame and the adjustment tube (Exhibit A-8). Once we gave him the go-ahead, he found the springs, and turned out the necessary parts on a lathe before the morning was over.

As we progressed through fabrication of the tiny and complex mirror mount pieces, the small group of designers, machinists, and engineers quickly became a tight-knit and efficient team. Things went very smoothly, and within one week, about seventy working hours, we made up two days of schedule slippage that had occurred earlier.

As the mirror mounts approached completion, Dan Rodenberger asked me to be responsible for design of the laser baseplates. The baseplates were aluminum slabs upon which the lasers, modulator, mirror mounts, and adjustment tools were mounted. The baseplates also had to be water cooled so the operating temperature of the laser could be adjusted easily by varying the water temperature. The baseplates were designed and fabricated within a period of four days.

The breadboard hardware was to be completed and ready for assembly on Monday morning, 26 June. The final part was completed the previous Saturday when Jack gave it to me at 4:30 in the afternoon.

That evening I took my wife out to dinner to celebrate the end of the long work weeks which had everaged over 60 hours for most of the project personnel. Before we left, I weighed myself on the bathroom scale, the first time I had done so since before the project began. I had lost fifteen pounds.



APPLICATIONS TECHNOLOGY SATELLITE - LASER COMMUNICATIONS EXPERIMENT

TRANSMITTER LASER 10.6 Microns

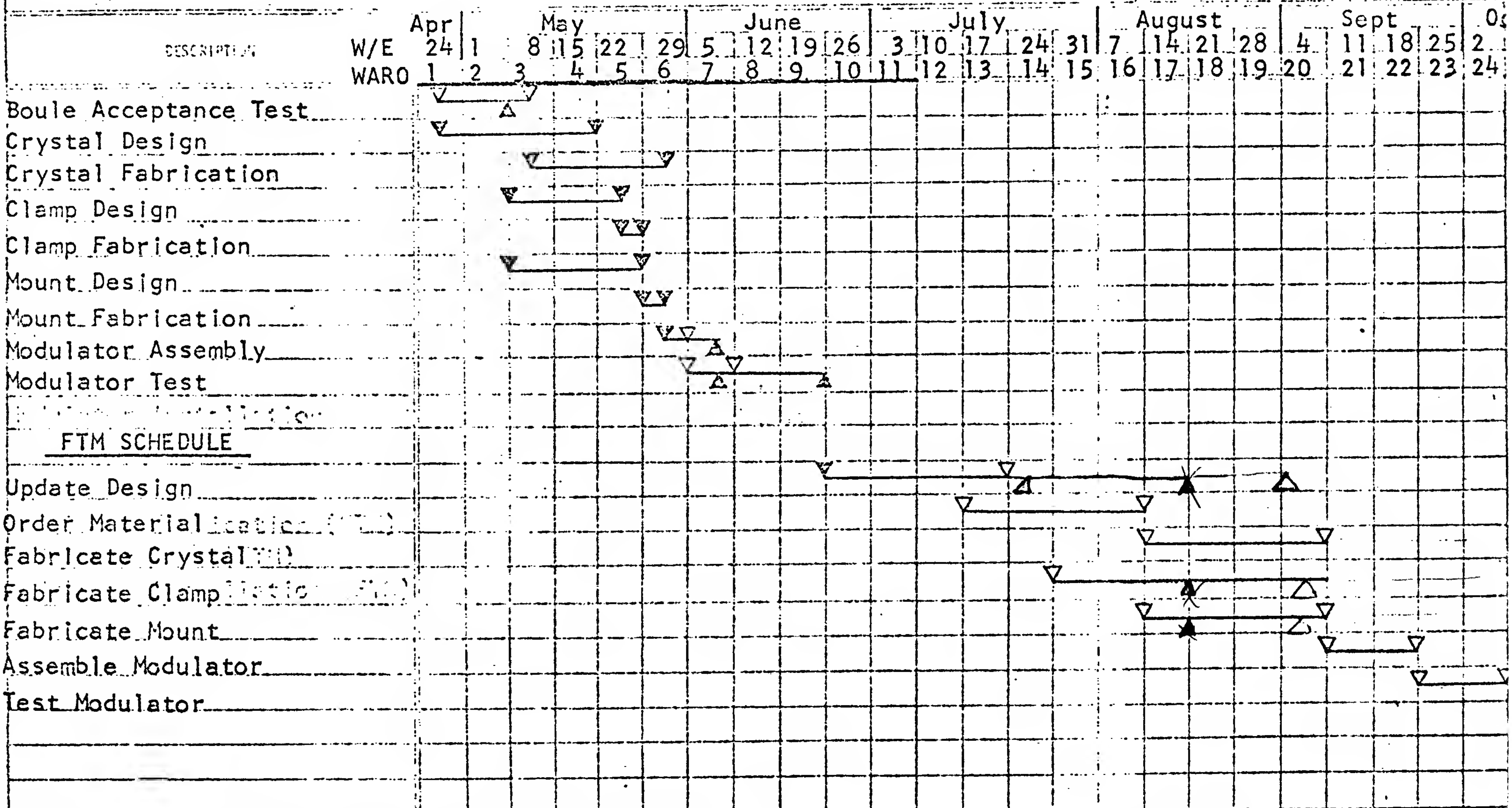
EXHIBIT A-1

Modulator SCHEDULE

7/6/70	3
ATS/LCE Program BB & FTM Modulator	
AGC	2400, 3400 3830, 4400
MWS/JAB	JWH

MODULATOR SCHEDULE
(Shown here in revised form - Note date)

EXHIBIT A-2



Notes

▽ = Official Schedule Start & Complete Dates
△ = Actual or Anticipated S & C Dates

▼ = Completed
▽_△ = Slippage In Date

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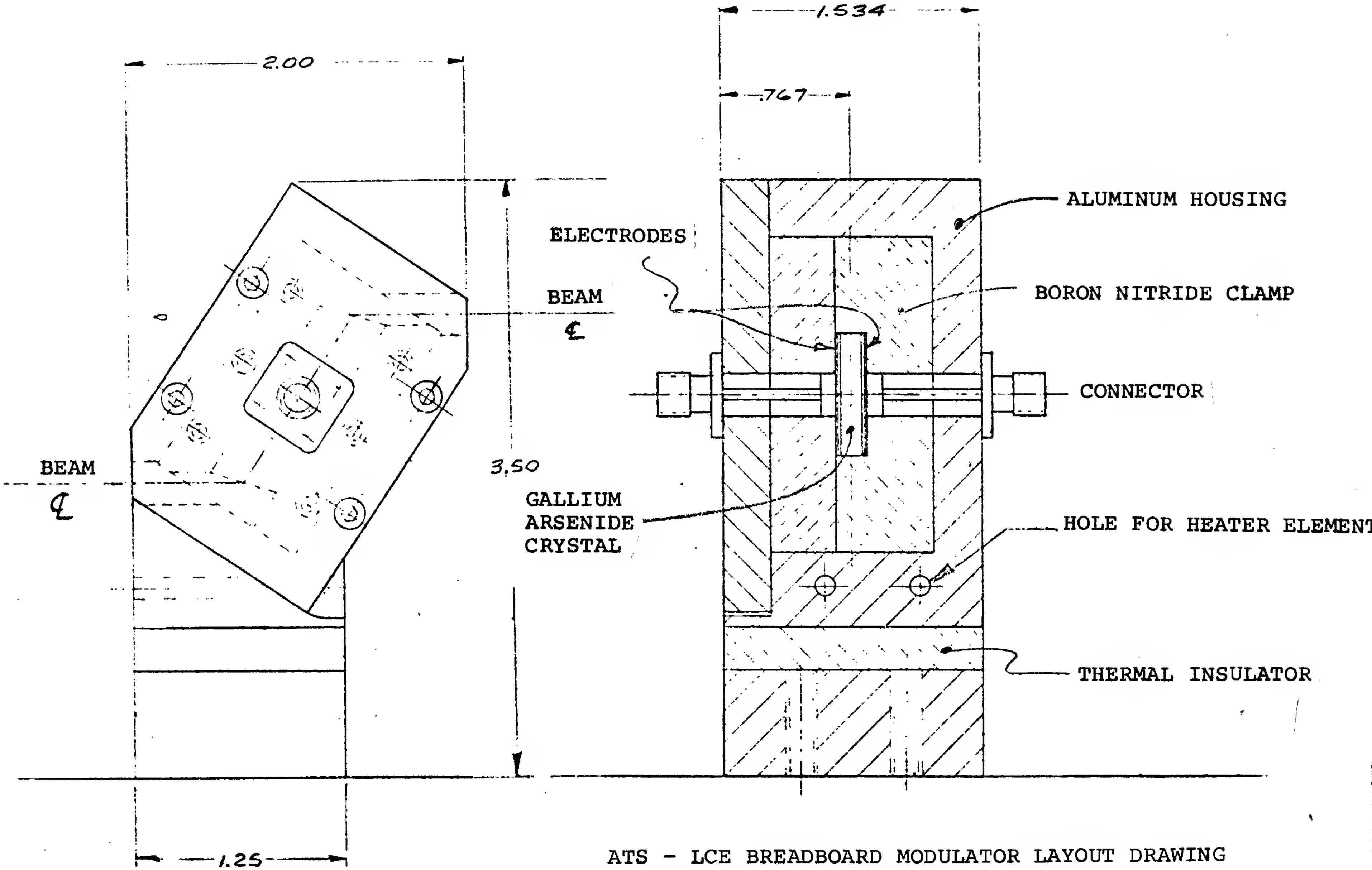
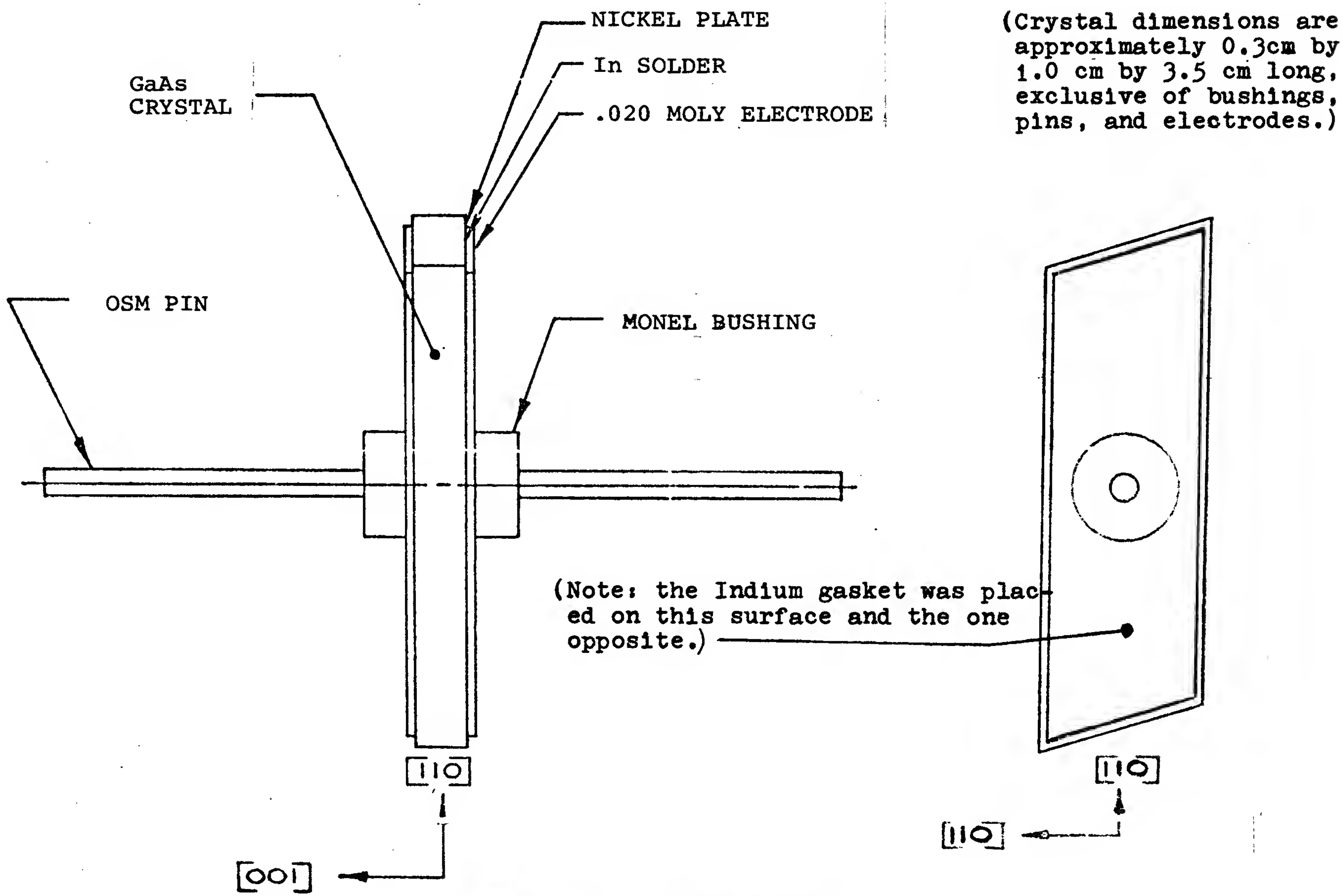


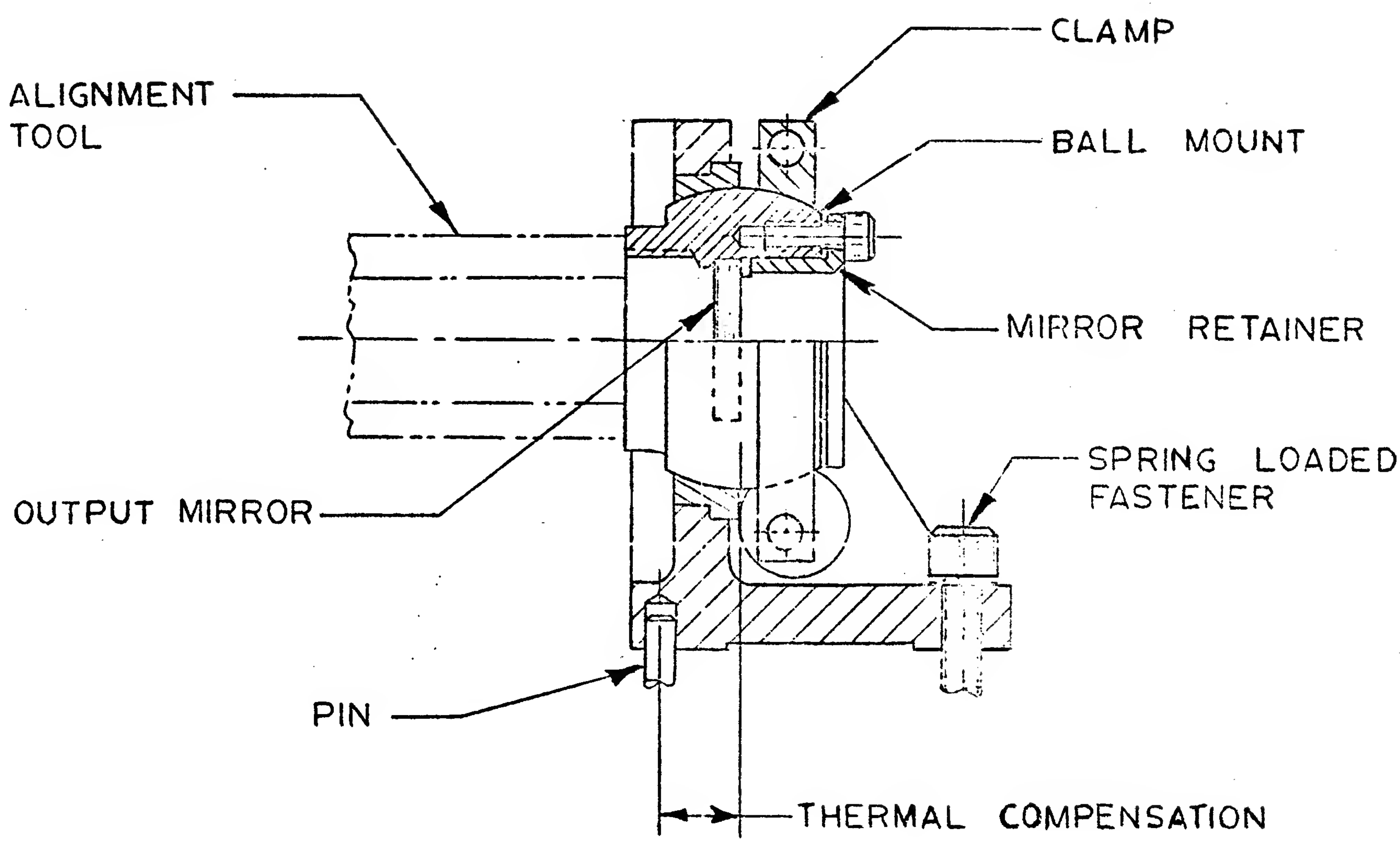
ATS - LCE BREADBOARD MODULATOR LAYOUT DRAWING

EXHIBIT A-3



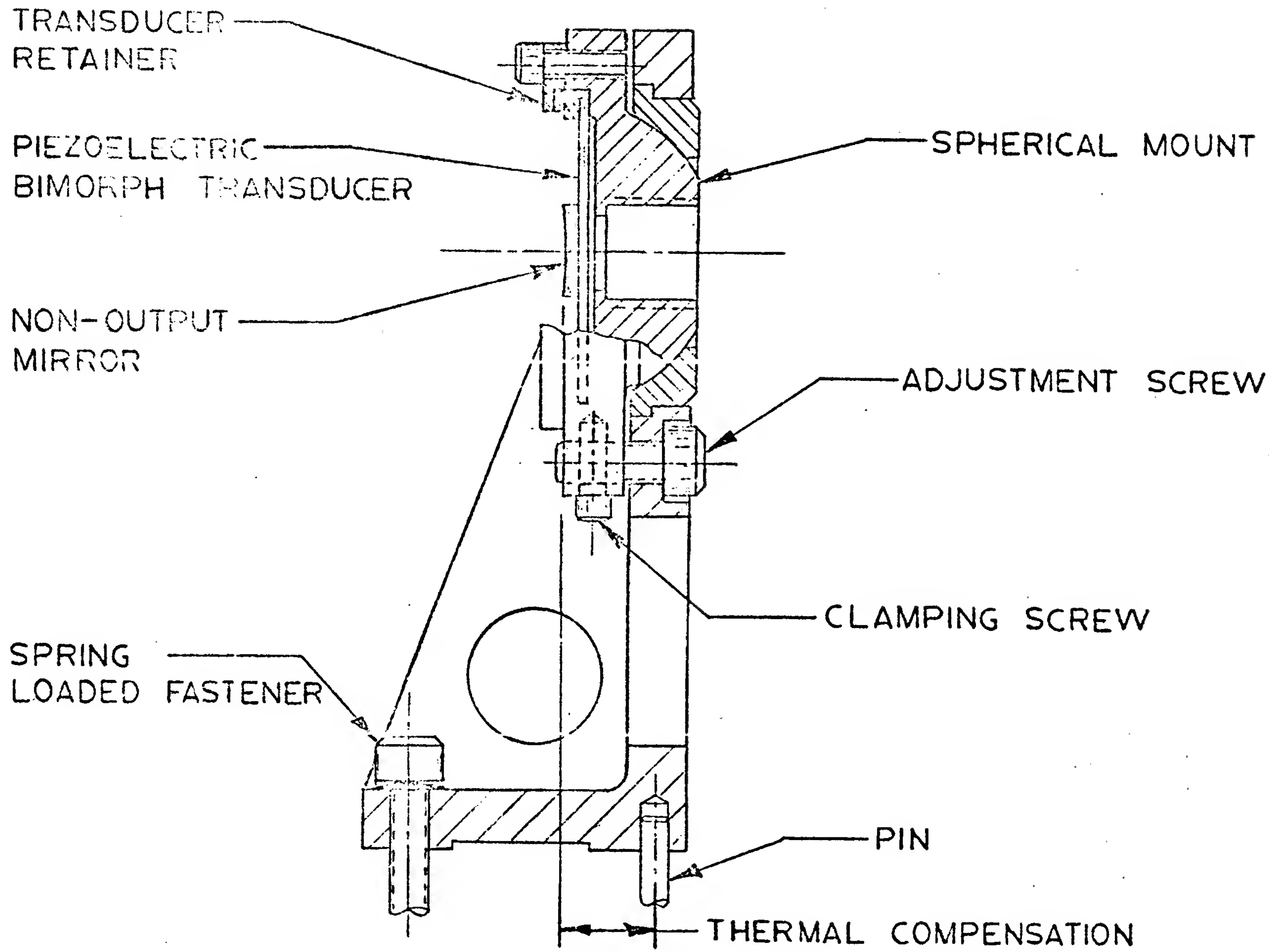
MODULATOR CRYSTAL ASSEMBLY

EXHIBIT A-4



OUTPUT MIRROR MOUNT

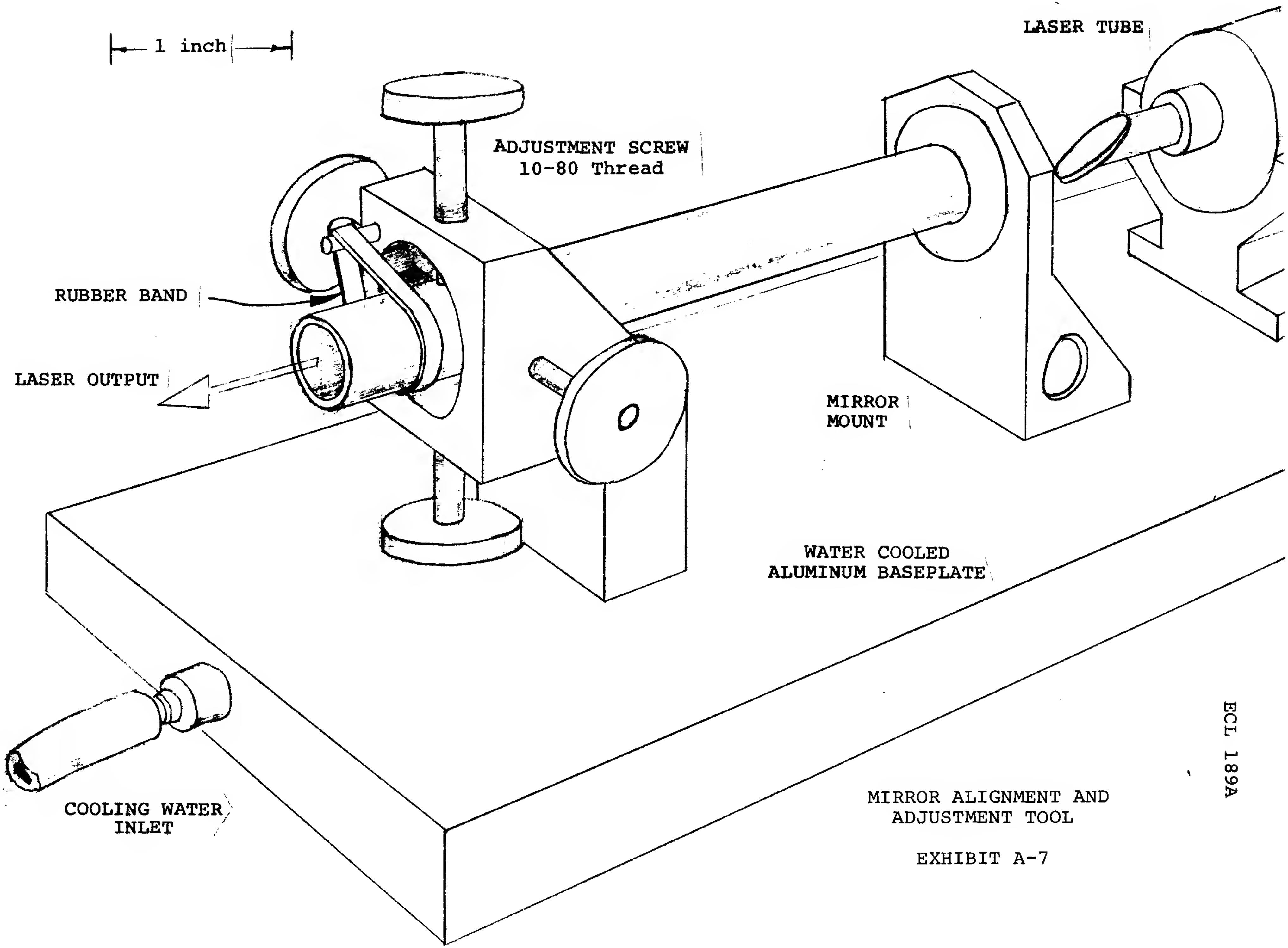
EXHIBIT A-5



NON-OUTPUT MIRROR MOUNT

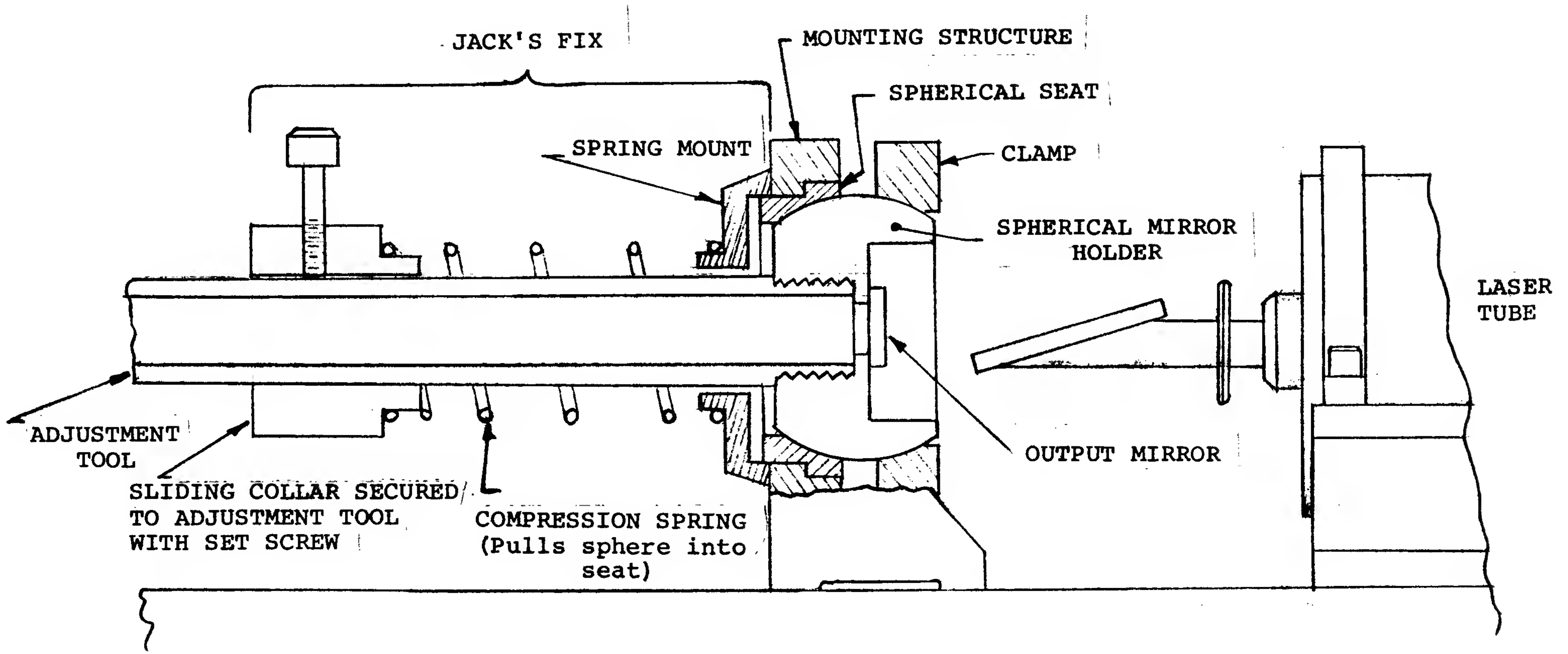
EXHIBIT A-6

ECL 189A



MIRROR ALIGNMENT AND
ADJUSTMENT TOOL

EXHIBIT A-7



JACK'S FIX FOR THE MIRROR MOUNT AND ADJUSTMENT TOOL

EXHIBIT A-8

LASER HARDWARE (B)

Contact Resistance and Materials

While the breadboard hardware for the Laser Communications Experiment was being fabricated, Fred Moreno started thinking about the Functional Test Model which had to be designed and produced next. To meet the schedule for the breadboard, Fred and others had taken many short cuts since it was only necessary to demonstrate feasibility. Many problems were recognized and expedient solutions were used with final solutions being put off for later study.

As Fred relates, the Functional Test Model was another matter:

From the outset the FTM design was an entirely different ball game from the breadboard. In the breadboard, we could be fairly quick and dirty, choosing materials and components as we wished, and ignoring those problems we couldn't find a quick answer for. The FTM was, on the other hand, a full-blown design program in which all the problems of vibration, thermal effects, hard vacuum (with the associated problems of evaporation and sublimation of materials) and reliability would have to be met. We would have to design with all these problems in mind, and we were further restricted by being able to use only those components that had been space qualified and were on a Qualified Parts List.

I began this phase by making a thorough analysis of the thermal contact resistance problem I had chosen to ignore previously. The problem of thermal contact resistance arises every time two pieces of equipment are bolted to one another. Even if the mating surfaces are carefully machined to maintain flatness and minimize roughness, there is still a thermal resistance at the interface whose value is difficult to predict. This problem caused me some concern because the laser tubes are cooled almost entirely by conduction, as is the modulator, and all the conduction heat flow must pass through a contact resistance occuring at the interface of the tube mount and the baseplate upon which all the equipment was mounted. It was necessary that this resistance be accurately known so that the tube performance (which varies with temperature) could be predicted. I carefully reviewed the literature again and collected some additional articles I had missed the first time. I went through each of these and culled out the pertinent information. I was disturbed at the lack of generality that occurred in most of the

available analyses. The more general works were the most theoretical, but required data not normally available, and therefore less useful. Most disturbing was the fact that none of the prediction techniques published agreed with one another when applied to my problems, often differing by a factor of 2 or 3.

I spent a day in the NASA Ames library, and turned up a NASA report on the subject written some years earlier. It gave results about in the middle of the range predicted by the others. Since it was published by NASA and our contract was for NASA, I felt very comfortable using it. Again using the programmable calculator, I made a parameter study and plotted the results so I could get a feel of what would happen if we changed designs, dimensions, or materials. The results are shown in Exhibit B-1.*

Once I had a handle on the contact resistance problem, I began studying the problem of evaporation and sublimation of materials in the hard space vacuum. It seems that under the condition of vacuum, many materials sublimate and condense on the interior surfaces of the spacecraft, sometimes with poor results. Our problem was doubly bad, because not only did we have to hold sublimation down to prevent problems in the spacecraft, but we would have to hold it low enough to prevent any deposition on the laser optics.

Several more trips to the local libraries gave me some information to get started. I finally found a series of reports that actually measured the sublimation rates on many materials. (Exhibit B-2) We used this list and some of the other reports as guidelines for the materials we could use. In metals, cadmium and zinc (thus brass) were out. Magnesium should be plated with nickel if it is used. Virtually all plastics were out. This made selection of wire insulation difficult until we found a class of Teflons that would do the job.

**J. J. Foti, "Analysis of Variables Affecting Thermal Resistance of Contacting Surfaces," Apollo Project Report No. 4-13, May 27, 1964.*

THERMAL CONTACT RESISTANCE - VACUUM

The curves on the following pages show the character of the thermal resistance caused by the interface of two metal surfaces in vacuum. The curves are based upon the analysis of FOTI (1) who generated the following empirical relationship:

$$R_{cv} = \frac{(8+e^{d})(Y_o x10^{-3}+16)^{0.34}\ (W_o x10^{3}+10)^{1.7}}{(3x10^{3})(8.9+0.1e^{d})\ F(P_a)\ G(S_f)}$$

where R_{cv} = thermal contact resistance (vacuum) °F-ft²/watt

P_a = apparent contact pressure, psi.

d = distance between clamping points, in.

S_f = surface finish of lower yield point surface, μ in.

Y_o = initial yeild point of material on hot side of interface, psi.

W_o = initial total flatness, in.

$F(P_a) = 0.5 + 0.1\ P_a \qquad 2 \le P_a \le 10$

$= 0.85 + 0.065\ P_a \qquad 10 \le P_a \le 30$

$= 1.8 + 0.034\ P_a \qquad 30 \le P_a$

$G(S_f) = 0.64 + 0.03\ (S_f \times 10^6) \qquad S_f < 12\ \mu$ in.

$= 1 \qquad 12\ \mu \text{ in} < S_f < 46\ \mu$ in.

$= 0.79 - 0.0046\ (S_f \times 10^6) \qquad 46\ \mu\text{in} < S_f$

EXHIBIT B-1

Reproduced from Fred's File

In air, the thermal contact resistance is given as

$$R_{ca} = \frac{R_{cv}(W_o + 32\ R_{cv}K_a)}{W_o}$$

where R_{ca} = contact resistance in air °F-ft^2/watt

K_a = thermal conductivity of air, BTU/hr-ft-°F
= (0.015 at S.T.P.)

As an example, for the baseplate of the ATS Tx LASER,

d = 0.75", P_a = 1000 psi, Y_o = 20,000 psi (aluminum),

S_f = 12-46 μin, W_o = 0.002 in, then R_{cv} = 0.34 °F/in^{2}watt

Further information may be obtained from the following sources:

(1) FOTI, J. J., "Analysis of Variables Affecting Thermal Resistance of Contacting Surfaces," Apollo Project Report M4-13, May 27, 1964.

(2) LAMING, L. C., Thermal Conductance of Machined Metal Contacts, Part I of International Developments of Heat Transfer Conference, 1961, Boulder, Colorado).

(3) PETRI, F. J., An Experimental Investigation of Thermal Contact Resistance in a Vacuum, ASME Paper 63-WA-150.

(4) FRIED, E., Thermal Joint Conductance in a Vacuum, ASME Paper 63-AHGT-18.

(5) STUBSTAD, W. R., Measurements of Thermal Contact Conductance in a Vacuum, ASME Paper 63-WA-150.

(6) FRIED, E., and F. A. COSTELLO, "Interface Thermal Contact Resistance Problem in Space Vehicles," ARS Journal, Feb. 1962.

F. Moreno
25 May 1970

EXHIBIT B-1

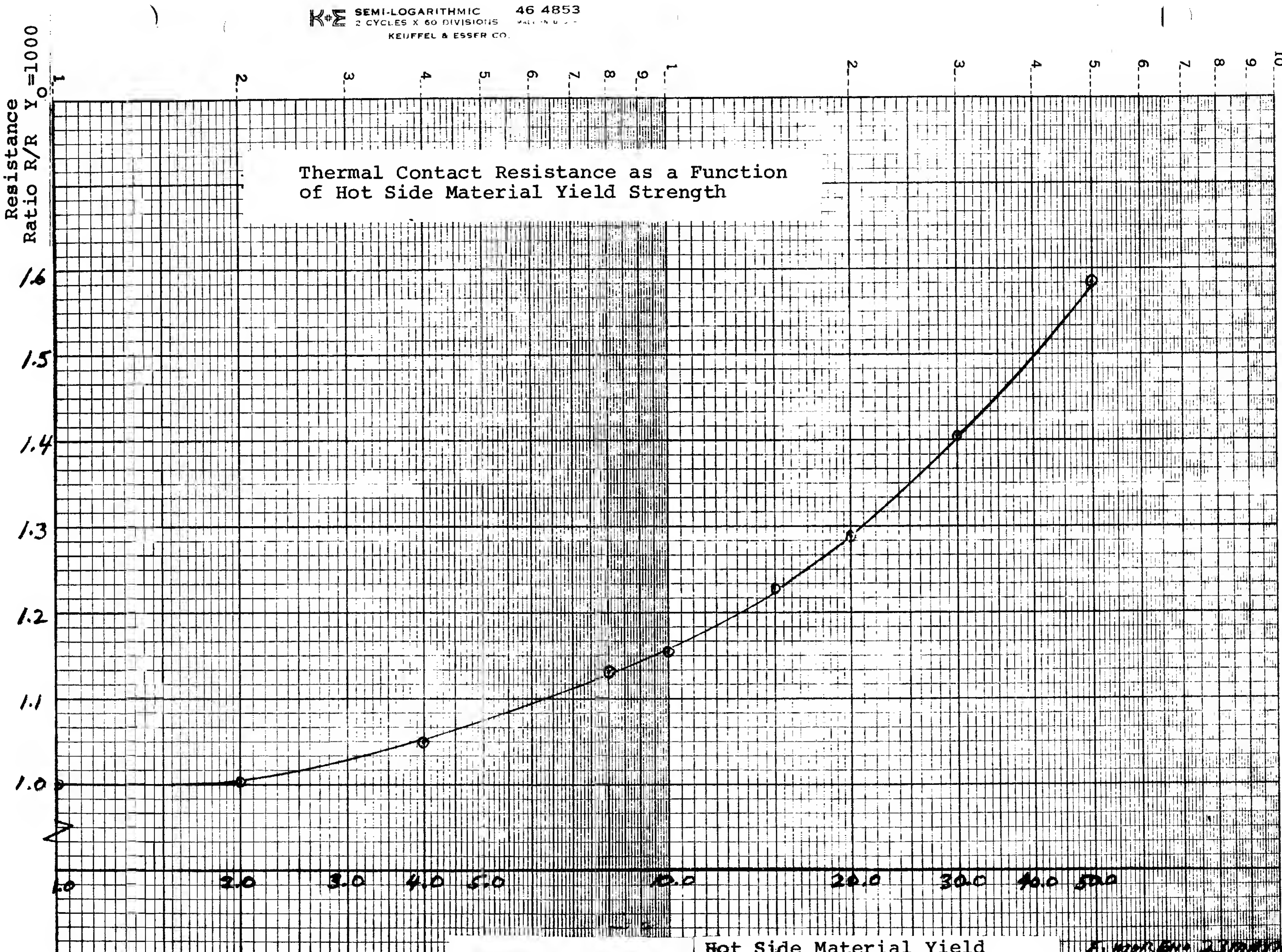
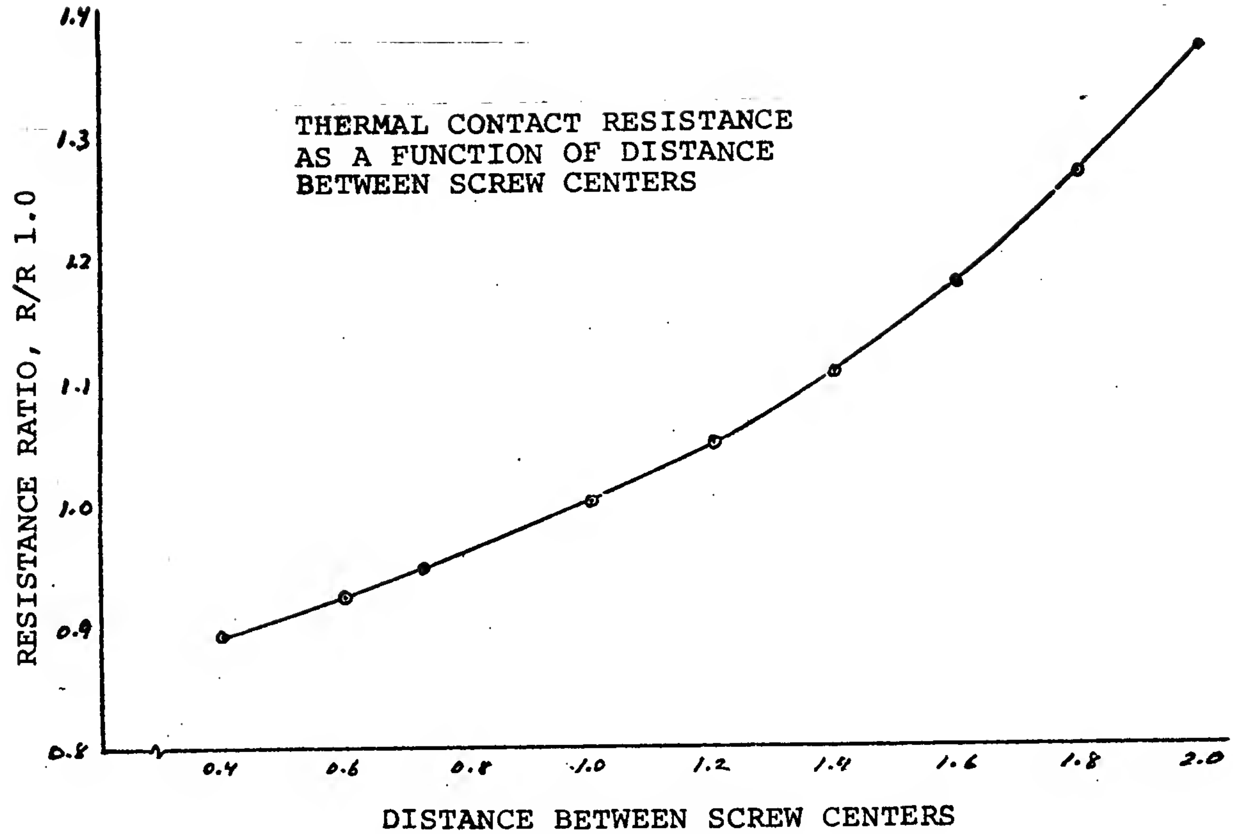

K+E SEMI-LOGARITHMIC 2 CYCLES X 60 DIVISIONS KEUFFEL & ESSER CO. 46 4853
Thermal Contact Resistance as a Function of Hot Side Material Yield Strength
Resistance Ratio R/R Y$_o$=1000
1.6
1.5
1.4
1.3
1.2
1.1
1.0
1.0
2.0
3.0
4.0
5.0
10.0
20.0
30.0
40.0
50.0
Hot Side Material Yield Strength, P.S.I. x 10^{-3}

EXHIBIT B-1


THERMAL CONTACT RESISTANCE
AS A FUNCTION OF DISTANCE
BETWEEN SCREW CENTERS
RESISTANCE RATIO, R/R 1.0
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
DISTANCE BETWEEN SCREW CENTERS

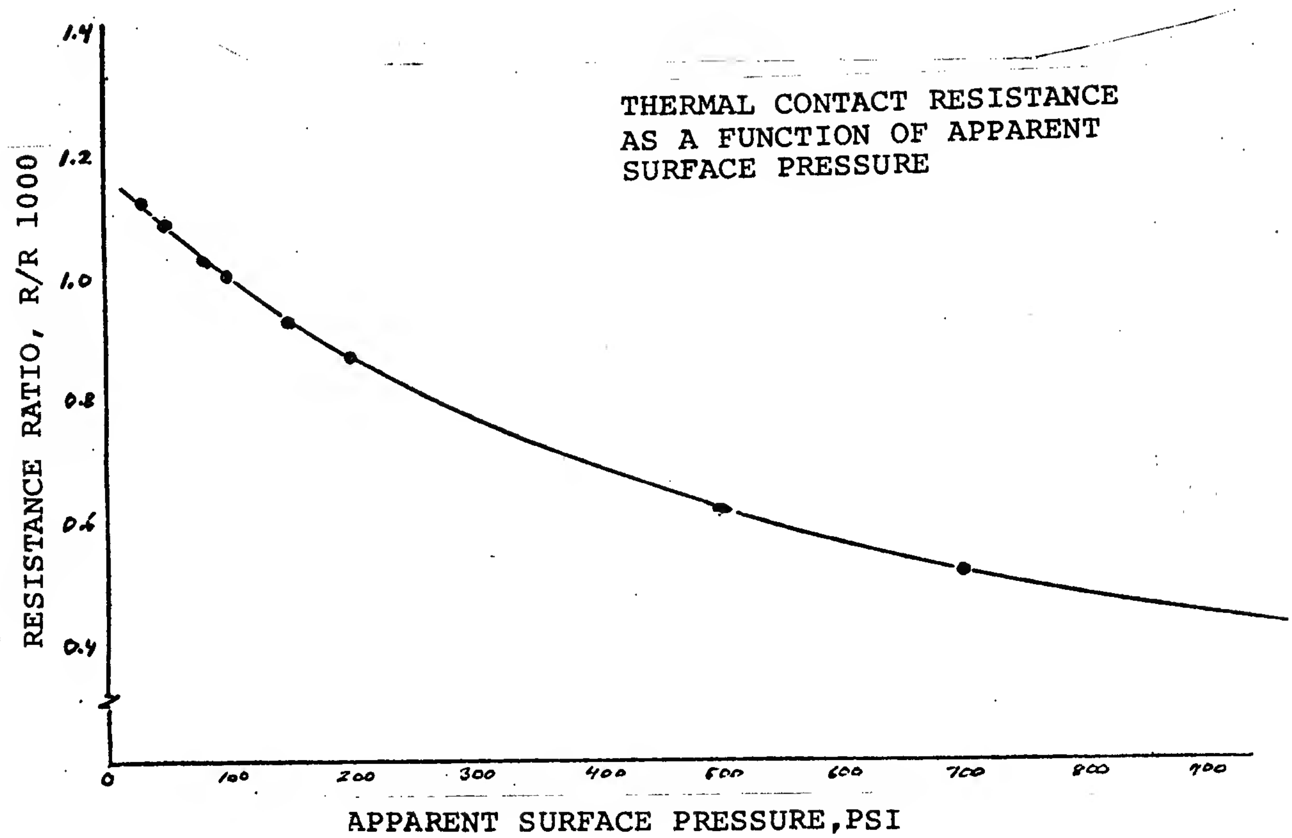
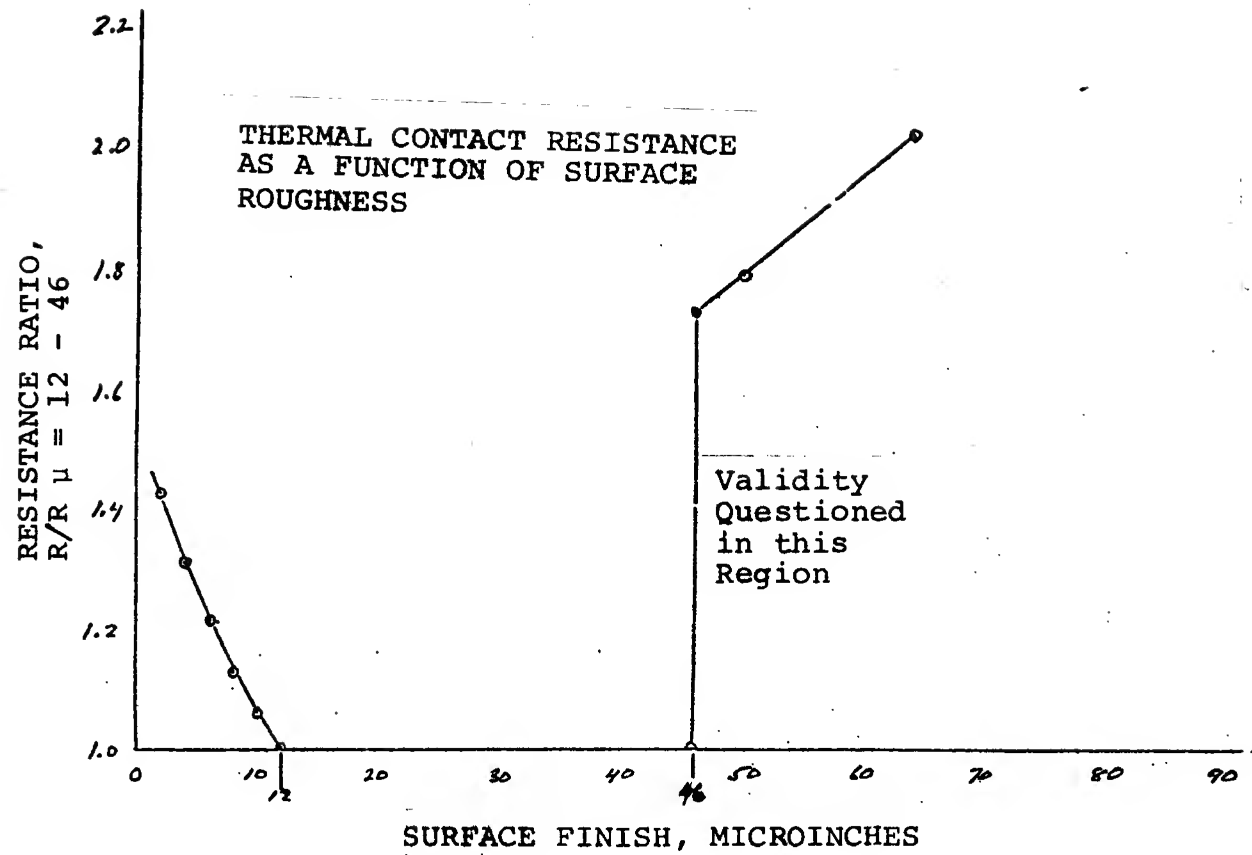

THERMAL CONTACT RESISTANCE
AS A FUNCTION OF APPARENT
SURFACE PRESSURE
RESISTANCE RATIO, R/R 1000
1.4
1.2
1.0
0.8
0.6
0.4
0
100
200
300
400
500
600
700
800
900
APPARENT SURFACE PRESSURE,PSI

EXHIBIT B-1


THERMAL CONTACT RESISTANCE
AS A FUNCTION OF SURFACE
ROUGHNESS
RESISTANCE RATIO,
R/R μ = 12 - 46
Validity
Questioned
in this
Region
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0
10
12
20
30
40
46
50
60
70
80
90
SURFACE FINISH, MICROINCHES

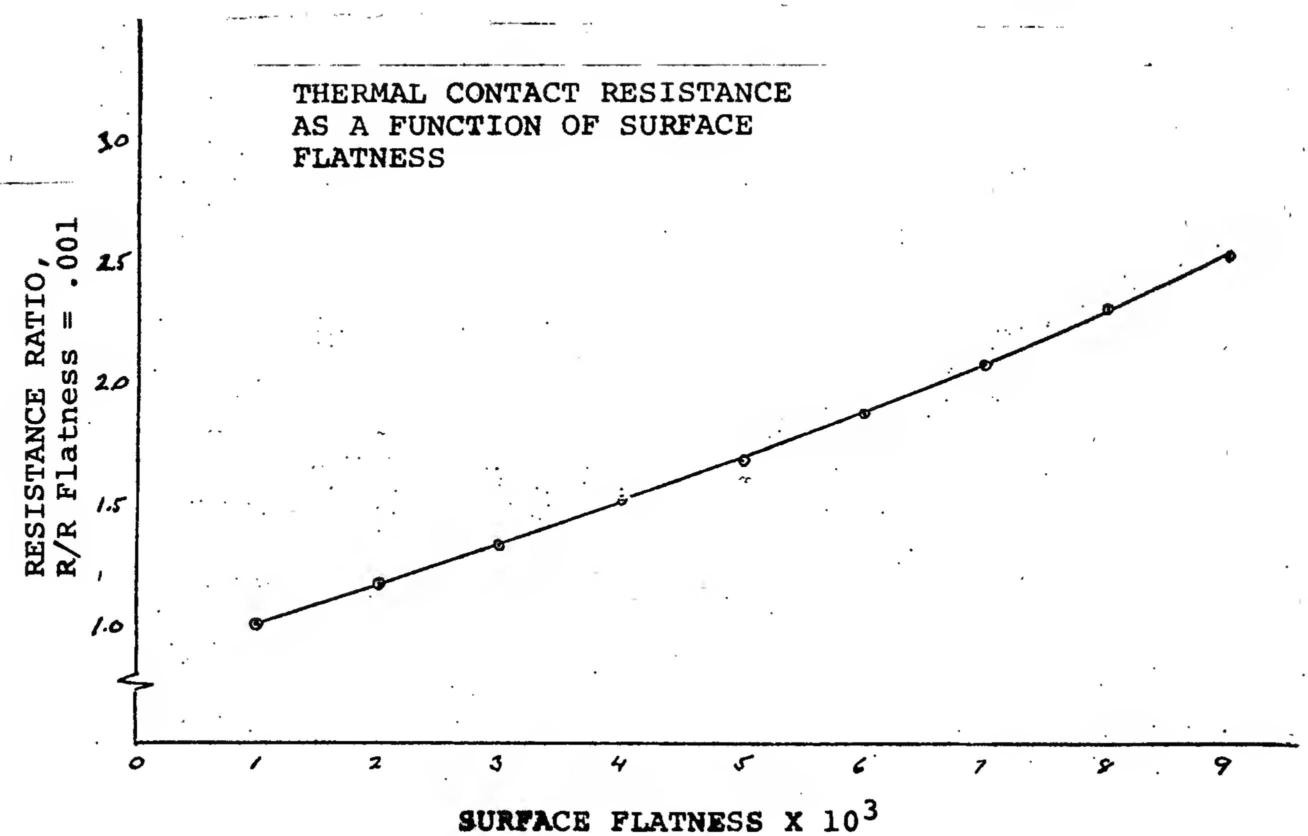

THERMAL CONTACT RESISTANCE
AS A FUNCTION OF SURFACE
FLATNESS
RESISTANCE RATIO,
R/R Flatness = .001
3.0
2.5
2.0
1.5
1.0
0
1
2
3
4
5
6
7
8
9
SURFACE FLATNESS X 10^3

EXHIBIT B-1

Excerpts from "Materials for the Space Vacuum", a report by Clarence E. Jahnke, Raytheon Co., Bedford, Massachusetts, September 1963

Guidelines for Selecting Metals, Ceramics, and Plastics

Like so many of the problems of space flight, that of materials selection for long exposure to a high vacuum is made doubly difficult by a general lack of reliable information. Most spececraft are not recovered; on those which are recovered, much of the evidence about vacuum effects on materials is destroyed during re-entry: and much of the little evidence that survives re-entry is highly classified. To a large extent, therefore, the designer must rely on laboratory data and speculation.

Two basic processes must always be considered when solid materials are being chosen for space applications: sublimation and outgassing. Both proceed differently in a high-vacuum environment than under normal conditions.

Sublimation is enhanced by vacuum, since molecules have extremely long mean free paths.

FROM THE MATERIALS RESEARCHER'S VOCABULARY

ABSORPTION: Penetration of a substance into the body of another.
DIFFUSION: Migration of atoms of one substance into another substance.
EVAPORATION: Conversion of a liquid into a gas.
MEAN FREE PATH: Mean distance traveled by a molecule of gas between successive collisions.
OUTGASSING: Release of gases from materials.
RHEOLOGY: Science of the flow of matter; the study of elasticity, viscosity, and plasticity.
SUBLIMATION: Conversion of a solid into a gas without the intermediate formation of a liquid.
VAPOR PRESSURE: Pressure of a confined body of vapor (depends only on temperature).

EXHIBIT B-2

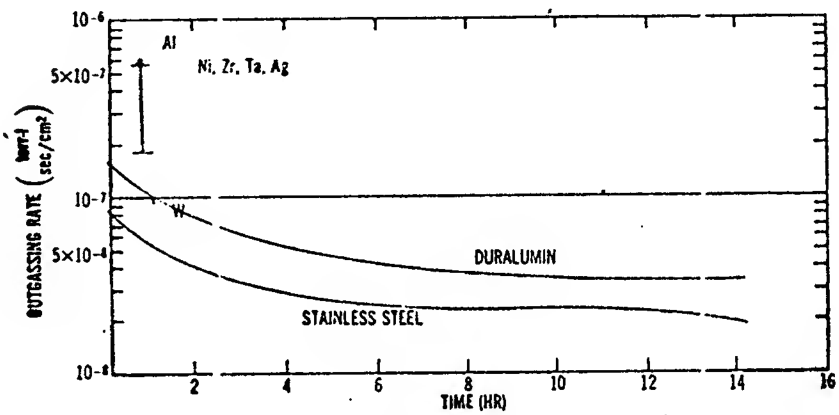
The special outgassing effects of the space vacuum influence the creep-rupture time relationship, fatigue life, and friction. NRL's Dr. M. R. Archer reports that, at high stresses and low temperatures, the creep-rupture time of metals is longer in vacuum than in air, while at low stresses and high temperatures, the relationship is reversed. (What constitutes "low" and "high" temperatures of course depends on the material.) He also notes that in space, the low density of the surrounding gas affects the fatigue life of certain materials, and particularly that of metals.

The removal of absorbed surface gases in space naturally leads to lubrication problems, for it invalidates the classical laws of sliding friction. In their place, modern friction theory can be used, which is based on the fact that the frictional force is a function of the actual area of contact, which in turn is determined by the rheological properties of the material. Even so, the problem of friction in space remains very complex and, for the purpose of equipment design, probably is best solved empirically.

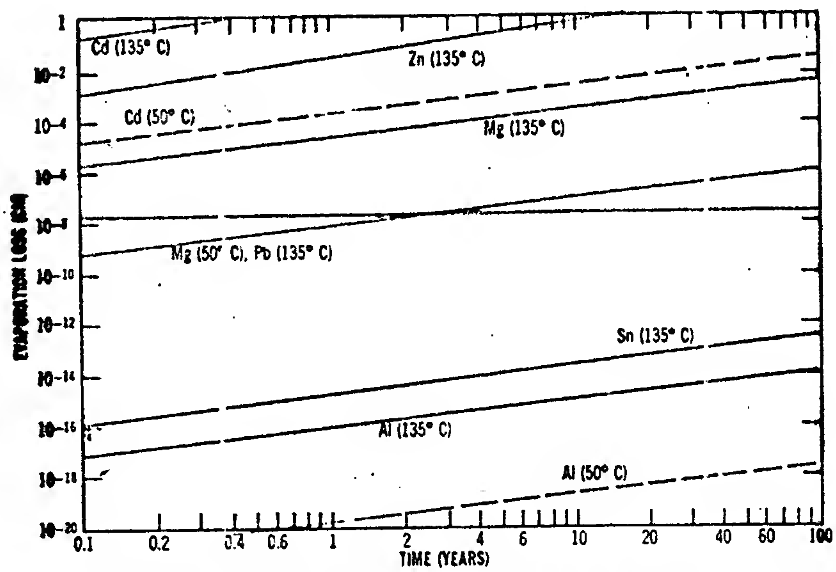
Metals Recommended for Space Applications*

Magnesium (with restrictions)	Chromium	Platinum
Silver	Iron	Iridium
Tin	Palladium	Zirconium
Aluminum	Cobalt	Molybdenum
Beryllium	Nickel	Rhenium
Copper	Titanium	Tantalum
Gold	Vanadium	Tungsten
	Rhodium	

*In order of decreasing vapor pressure.



OUTGASSING of metals in high vacuum



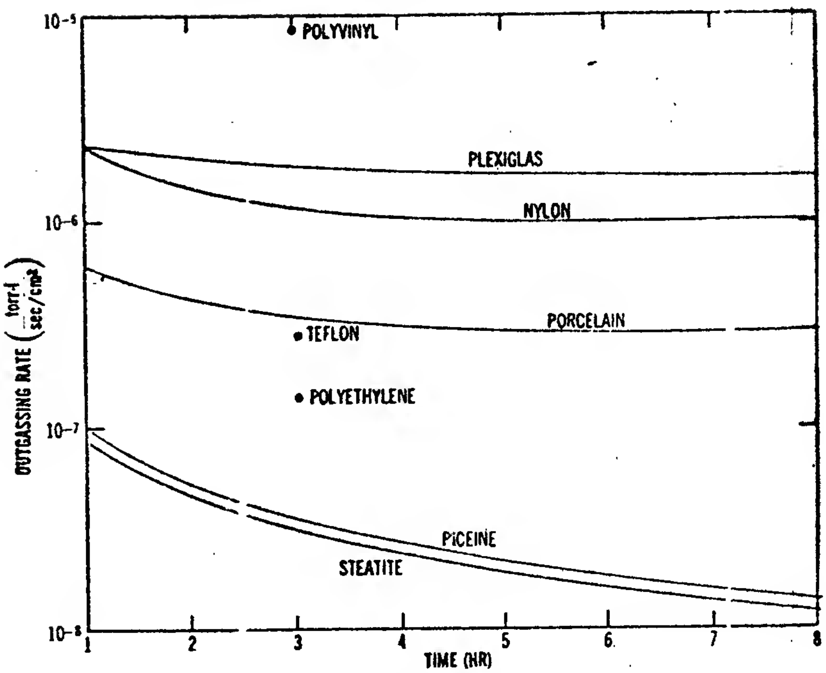
THEORETICAL sublimation of some metals in high vacuum

RATE OF OUTGASSING

The exact mechanism of outgassing is still a matter of controversy. The behavior of pure metals in space can be predicted with reasonable certainty from the Langmuir equations.

Tin is recommended as a plating material to inhibit sublimation.

EXHIBIT B-2



OUTGASSING of plastics and ceramics in high vacuum

The chemically more stable ceramics generally have excellent thermal and electric properties for space applications. Used by themselves, they are not very strong, but on metal substrates they show physical properties that sometimes exceed those of metals. Steatite and other ceramics are recommended as electric insulation for spacecraft equipment. Generally the ceramic oxides and compounds of aluminum, beryllium, chromium, magnesium, silicon, thorium, titanium, and zirconium appear suitable for space applications.

Their behavior in vacuum puts the silicon polymers in a class by themselves. They are more heat resistant than organic plastics and have higher dielectric strengths, and their resistance to mechanical shock and vibration is good. Their mechanical strength, though, is low.

The suitability for vacuum service plastics in general is one of the most controversial subjects in the entire materials field. For one thing, the almost complete lack of standardization in the plastics industry makes it very hard to analyze the final product. Every manufacturer seems to have his own plasticizer, dyes, and other additives, and the available test data in many cases are very contradictory.

Nevertheless, there are some basic guidelines for the selection of plastics for space application. Plastics formed by polymerization of pure materials are satisfactory, while plastics using a plasticizer should be avoided. Neoprene is not recommended, because of its prohibitive rates of outgassing and sublimation, but the fluorocarbons seem desirable. Both Teflon (tetrafluoroethylene) and Kel - F (trifluorochloroethylene) have been used extensively in satellites.

EXHIBIT B-2

LASER HARDWARE (C)

The Functional Test Model

While I was studying the problem of contact resistance and evaporation, the breadboard was assembled and tested. It met all specifications and was delivered on schedule with award of full incentive fee. It turned out that both mirror mount designs were equally hard to lock down without changing the angular adjustment, but were not as difficult to work with as I had anticipated. I'm inclined to think it was more a function of talented technicians with the golden touch, and less a function of my design.

In contrast to the fever pitch of effort that was maintained during the breadboard phase, the Functional Test Model (FTM) phase began slowly. It was as if the project had taken on a personality of its own, and that personality was exhausted after the strenuous breadboard effort. Whatever the reason, things seemed to go very slowly at first, and the schedule began to slip badly. On July 2, I had completed the bulk of my analysis and I asked Dan Rodenberger what he wanted me to do. He asked me to be responsible for the design and analysis of the modulator. Mirror mount design would be handled by Steve Weaver, another mechanical engineer now available.

About this time I began to keep a personal log so that I had a personal record of what was going on.

At the beginning of the modulator detail design, I requested that a new designer, Tim Wallace, be brought on the job. I had worked with Tim on previous projects, and we worked well as a team. We began searching for a thermally insulating material for the modulator base that also could function as a structural support. On the breadboard, I had just glued a slab polypheneline oxide plastic on the bottom of the modulator, but for the FTM, glues, epoxies, and plastics were out. Teflon had excessive creep, and poor dimensional stability. We found no answers.

On August 3, I sketched what I thought the modulator should look like. (Exhibit C-1) I envisioned the housing as a milled aluminum assembly with side covers carrying electrical connectors for the crystal electrodes, and springs to hold the boron nitride in place. Radio frequency interference (RFI) filters had to be included to filter any electrical noise that might otherwise leak out of the modulator into the system electronics. Four filters were required: two for the heater leads, and two for the thermistor temperature control leads. We found a satisfactory small filter, but abandoned

it for an electrically identical, but physically larger and heavier filter which was space qualified.

Two days later, the optics people decided to change the length of the modulator crystal from 2.0 cm to 3.5 cm. This would result in additional weight in an already overweight assembly, without an increase in weight budget.

On August 10, it was decided to abandon boron nitride for the clamp in favor of high grade aluminum oxide. We would machine cavities in the Al_2O_3 clamp to compensate for its higher dielectric constant, and hopefully reduce the stray electrical capacitance to an acceptable level. NASA now informed us that use of indium gaskets was forbidden because they tended to pound out under vibration.

I wrote a memo to Dan Rodenberger listing six problems that I had not yet resolved (Exhibit C-2). I was leaving on vacation for two weeks, and I wanted to make sure some progress was made while I was gone. Things seemed to be getting steadily worse, and I felt I had picked a poor time for vacation, but my wife was to start school in September, and I couldn't schedule another time until Christmas.

Wednesday, August 19, I got a phone call at home from Dan. He asked me to come back and help as the schedule was slipping.

When I returned John Sullivan told me they planned to scrap the aluminum oxide idea because of our lack of experience with this material and return to boron nitride. We decided to perform a vibration test to check the characteristics of the soft boron nitride, and to check various clamping and restraining spring combinations. We would also try indium gaskets to see if they would pound and creep as NASA said they would. I calculated the "g" level necessary to generate the creep stress by converting the stress on the gasket into a force acting on the crystal, and then knowing the mass of the crystal, I calculated the "g" level using $F = ma$. The "g" level I obtained was far above the levels I anticipated during testings, so I predicted we should have no problems. I began designing a test fixture for the shake tests.

At the same time the electronics people wanted to know what total amount of energy would be required to heat the modulator in a given time from an ambient temperature (cold) start-up. This varies depending upon the maximum power available, and so I spent some time with the calculator generating the necessary figures and curves.

The following day I calculated the expected weight of the modulator. The electrical engineers concerned with shielding the system from modulator-generated electrical noise allowed us to substantially reduce the thickness of the housing walls with a corresponding reduction in weight. This gain was wiped out, however, by the increased crystal length. The expected weight was 0.68 pounds; the budget was 0.375 pounds. I began thinking about titanium screws to save weight.

A new problem surfaced. The optical engineers wanted dust covers over all the Brewster windows and mirrors. They feared that the high static voltage on the windows would attract dust floating in the weightless environment. The covers would have to be electrically non-conductive which ruled out metals, and just about everything else outgasses in vacuum; flexible to allow mirror adjustment; dust tight; and constructed to survive the launch environment vibration. My first comment on the dust cover problem was the same as all my comments on this problem for the rest of the project: "no way."

The vibration test equipment was finished August 27, and delivered from the shop. I prepared a detailed test plan for the engineers who would conduct the tests.

On September 1, the electrical engineers decided to change the electrical connectors from the OSM type (miniature) to the BNC type (large) arguing that they needed the electrical characteristics of the larger connector. I had more than a few choice words for these guys, and when I pointed out that we were having enough size and weight problems with the OSMs, they decided to reconsider.

At this time I made a decision concerning the thermal insulator for the modulator. I had used plastic on the breadboard for convenience, but the outgassing characteristics made it unsuitable for the FTM. After considering available materials, I decided to use a special machinable ceramic manufactured by Aremco Products, Inc. (Exhibit C-3). The ceramic had near perfect thermal conductivity for my application, and sufficient mechanical strength.

The vibration tests were completed September 4. The indium gaskets had performed successfully, but the boron nitride generated some dust at the contact with the springs. We decided to incorporate small teflon "baskets" that would sit between the springs and the boron nitride thus eliminating the dust due to abrasion. There wasn't time to test the new arrangement.

I had received a detailed description of the space allocations for our equipment from Aerojet on September 3 with a preliminary drawing of the laser communication experiment package. (Exhibit C-4) It was clear that the OSM connectors on the modulator stuck out too far, (Exhibit C-5) and some changes would be in order.

Tim Wallace and I grappled with the connector problem. We tried different arrangements to conserve space, but all our proposed solutions had flaws in them, either because of complexity, or because of difficulty of fabrication or assembly. Exhibit C-6 shows one of our sketchings. We checked out other, smaller connectors, but those that we found that would do the job were ruled out by the Reliability people because of lack of historical data, or lack of space qualification. The schedule continued to slip on all parts of the project, and everyone was under pressure to catch up. This didn't help the flow of ideas at all.

Finally on September 16 Tim and John came up with a solution to the connector problem. The idea was a real beauty. Tim proposed that we use the side of the modulator housing as a connector, rather than attaching one half of the connector to the housing and the other half to the cable. The new design (Exhibit C-7) would use a modified OSM connector with the nut removed. The modified connector was then soldered to the housing side, thus hard wiring the cable to the side. The overall dimensions of the modulator were dramatically reduced, and the new design easily fit within the Aerojet space allocation.

The machinists began to work on the machinable ceramic and quickly found that it didn't really live up to its name. It would chip and crack, but they were sure that they would learn how to handle the material. After several days of trying, they finally made a perfect part.

Meanwhile, Tim hurried to complete detailed fabrication drawings of the modulator. Analysis showed that tolerance stack-up could cause problems during assembly, and so he made numerous small changes in design to alleviate these problems.

About this time, Dan Rodenberger submitted his resignation to the company. He had assigned Steve Weaver to be responsible for the dust cover problem, but because of Steve's already heavy work load, he had done nothing about the problem in the previous weeks. When Dan left, Steve was made responsible for the entire mechanical design on the project, and on Oct. 1 he asked me to be responsible for the dust covers. I refused, explaining that I was already working long hours, and that I

thought the dust cover idea was a bad one. Several days later Aerojet told us they had decided to put a dust cover over the entire system to protect their telescope and associated optics. This eliminated the need for small dust covers on our equipment.

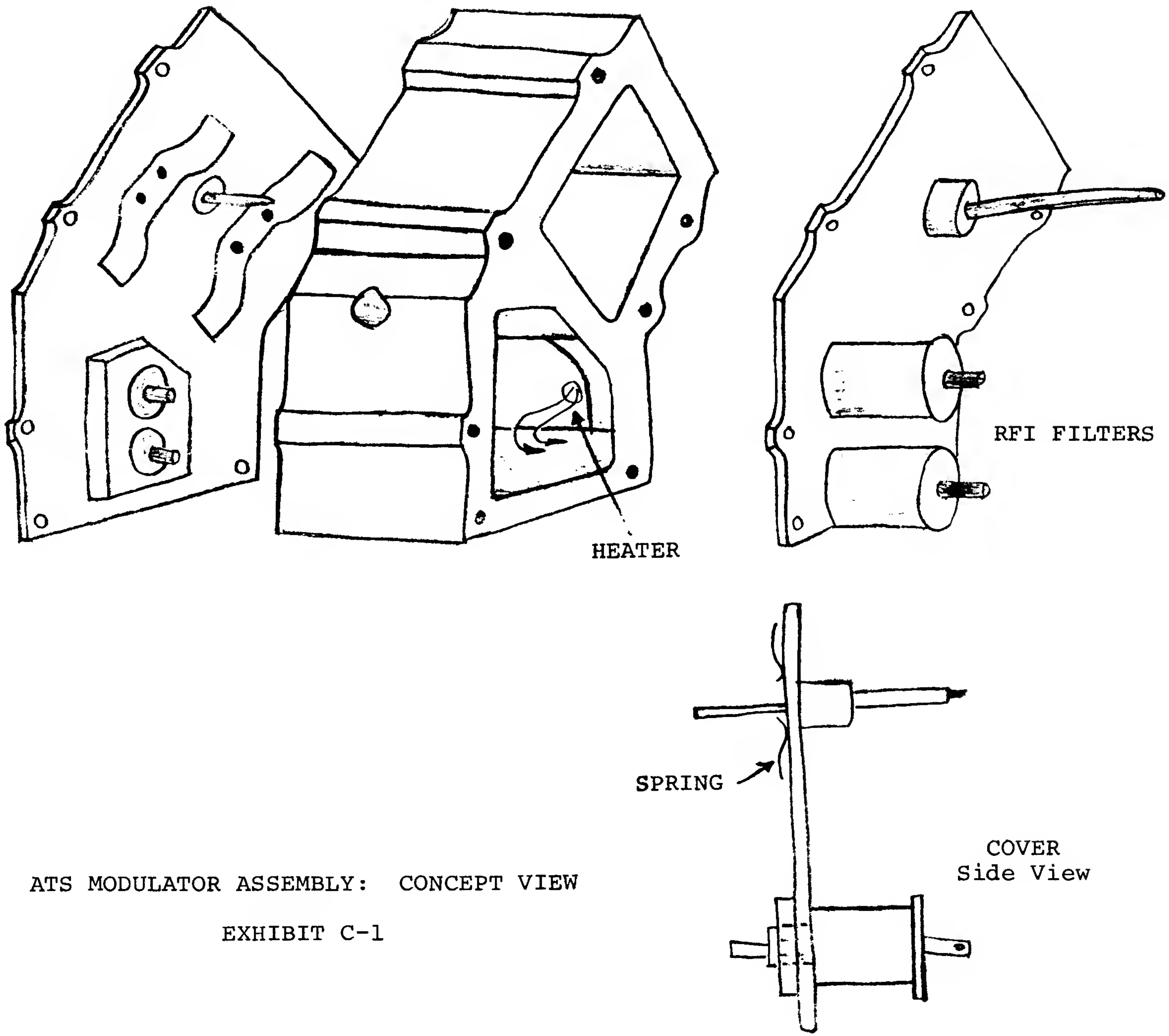
In the early days of October we built a dummy modulator to test for vibration; I was concerned about resonance in the fundamental mode which was within the range that we would have to test. A high level resonance could break the ceramic base. However, I felt that the construction of the modulator with its side covers would provide enough structural damping to prevent any large amplitude resonance. A vibration test of the dummy confirmed my guess; the resonance was clearly evident, but of low enough level as not to be harmful.

During the latter part of October and early November, I spent the bulk of my time checking parts as they were made and helping the technicians assemble the many tiny parts that went into the modulator. John and I had carefully checked Tim's drawings, spending two days catching and correcting subtle mistakes. Our checking was paying off as everything went together smoothly and accurately. By the end of the first week of November, the modulator was completely assembled and ready for testing. (Exhibit C-8)

By the first week of November, Sylvania and Aerojet had completed and submitted projected costs for the remainder of the job. This procedure is repeated at intervals throughout all contracts so that NASA can keep track of future expenditures. Sylvania projected a moderate cost increase due to a variety of problems. Aerojet projected a cost increase of several million dollars for their part of the job. This occurred at a time when NASA had its budget for the whole ATS program trimmed a substantial amount. After some deliberation NASA decided to terminate both the Sylvania and Aerojet contracts. On November 11, the program office issued stop-work notices to virtually all project personnel, and all work on the laser communications experiment ceased.

While NASA was forced to scrap the laser communications experiment for ATS-F and -G, they still expressed interest in developing space qualified CO_2 lasers. Sylvania submitted a proposal to develop these and subsequently won a contract for about a quarter of a million dollars. The idea of a smaller experiment was kicked around for a while, with Sylvania being considered for responsibility for the entire job,

but at the time this is being written (March 1971) no other contracts have been issued. The modulator and all the other laser communications experiment equipment (electronics, laser tubes, mirrors and mirror mounts, and associated optics) are still locked up in bonded stores, and there are at present no plans to use this equipment.



ATS MODULATOR ASSEMBLY: CONCEPT VIEW

EXHIBIT C-1

SYLVANIA
SYLVANIA ELECTRIC PRODUCTS INC.

SYLVANIA ELECTRONIC SYSTEMS
WESTERN DIVISION
P. O. Box 205, Mountain View, Calif. 94040

13 August, 1970
SES: 241-70

SUBJECT/DATE: ~~ATS~~ MODULATOR DESIGN

TO: D. Rodenberger

FROM: F. Moreno

I regret that because of a variety of problems, I have been unable to complete a detail design of the ATS modulator assembly. I will be on vacation from August 17th through 28th. During my absence, the following areas will require continuing attention:

1) The vibration tests on the boron nitride together with the various clamping arrangements proposed should be completed as soon as possible so that a final design may be completed.

2) Questions concerning the proposed thermal insulator material ("Aremcolox" ceramic made by Aremco Products, Inc.) must be resolved. The material has low thermal conductivity, low coefficient of thermal expansion, high compressive and flexural strength, and in some grades is easily machined in the unfired state. The material is used for vacuum tube insulators, and in other high vacuum installations. Reliability should examine the material, and a sufficient quantity ordered. J. Raffarin is familiar with this material, having used it in the past.

3) Qualification information for the heaters is still forthcoming.

4) Detail design of the cable terminations must be completed and the many small parts fabricated.

5) Mounting provisions for the dust covers must be included. There are at present no tentative designs for such covers or their mounts.

6) The specification drawing for the thermister, assembly is complete. The thermisters should be ordered immediately, as there is a four week delivery for custom assemblies.

Fred Moreno

Fred Moreno

FM:db

EXHIBIT C-2

AREMCOLOX™ MACHINABLE CERAMICS

Aremco now offers industry **five** basic machinable ceramics, available in standard rods and plates which can be readily fabricated into precision parts using conventional machine shop equipment. Prototype costs can be cut dramatically and development time reduced using these easy-to-fabricate Aremcolox materials. Complete processing instructions and technical assistance are offered by Aremco engineers for all Aremcolox materials.

Aremcolox machinable ceramics offer the designer a wide range of properties with temperature limits from 750°F to **2600°F**. . . enabling him to select the right grade for his application . . .

AREMCOLOX GRADE	TEMPERATURE LIMIT °F	GENERAL DESCRIPTION
502-400	750	Hard dense material, combine high strength with high dielectric properties, requires no post-cure.
502-600	1100	Dense, zero porosity, easily machined, highest dielectric properties, requires no post-cure.
502-1100	2100	Most versatile material, widest variety of standard shapes available, usable as recieved in unfired state to 1000°F. or easily fired after machining to harden and extend temperature limit to 2100°F.
502-1300	2200°F	Machinable as supplied. Offers unusual thermal shock resistance due to low thermal expansion rate . . . close to zero.
502-1400	2600°F	Machinable as supplied. Offers highest temperature resistance.

TYPICAL PARTS WHICH CAN BE MADE FROM AREMCOLOX CERAMICS

COMPONENTS

Microwave and vacuum tube insulators, substrates, transformer standoff, heating element holders, high temperature rocket components, etc.

TOOLING

High vacuum insulators, thin film jigs, semiconductor alloying boats, glass-to-metal sealing molds, furnace brazing fixtures, induction heating, soldering, spot welding and hot forming jigs, etc.

See reverse for data and pricing on all Aremcolox Machinable Ceramics.

9-1-72

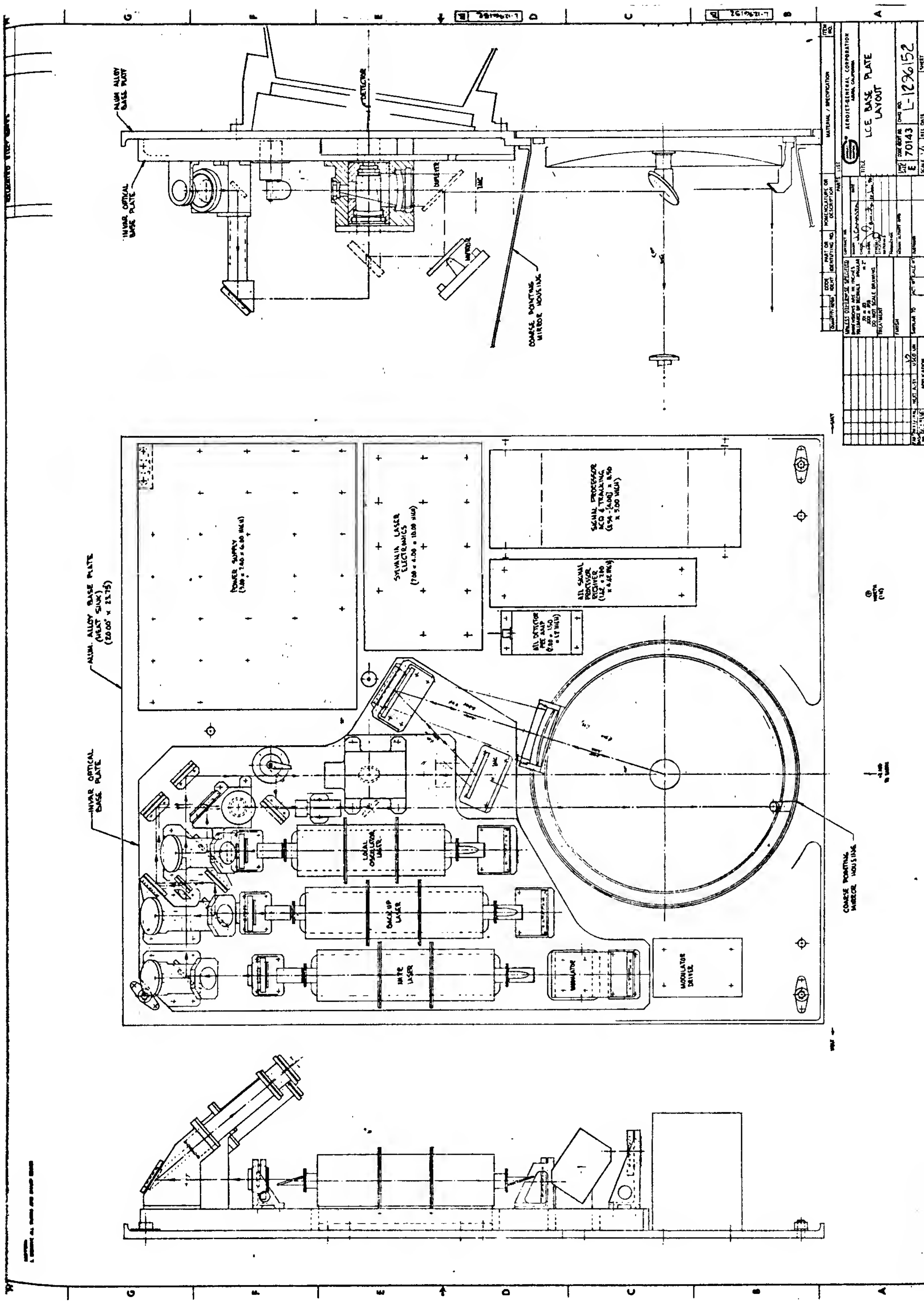
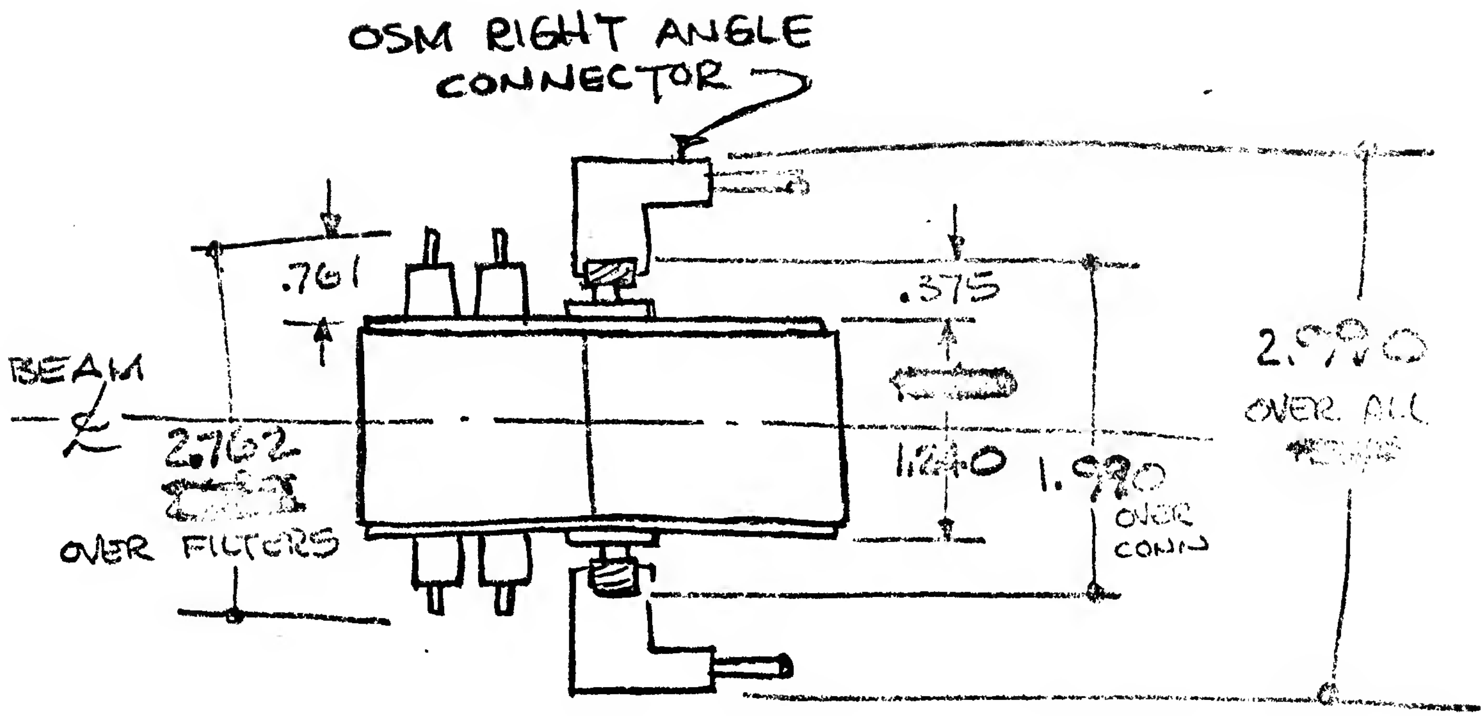
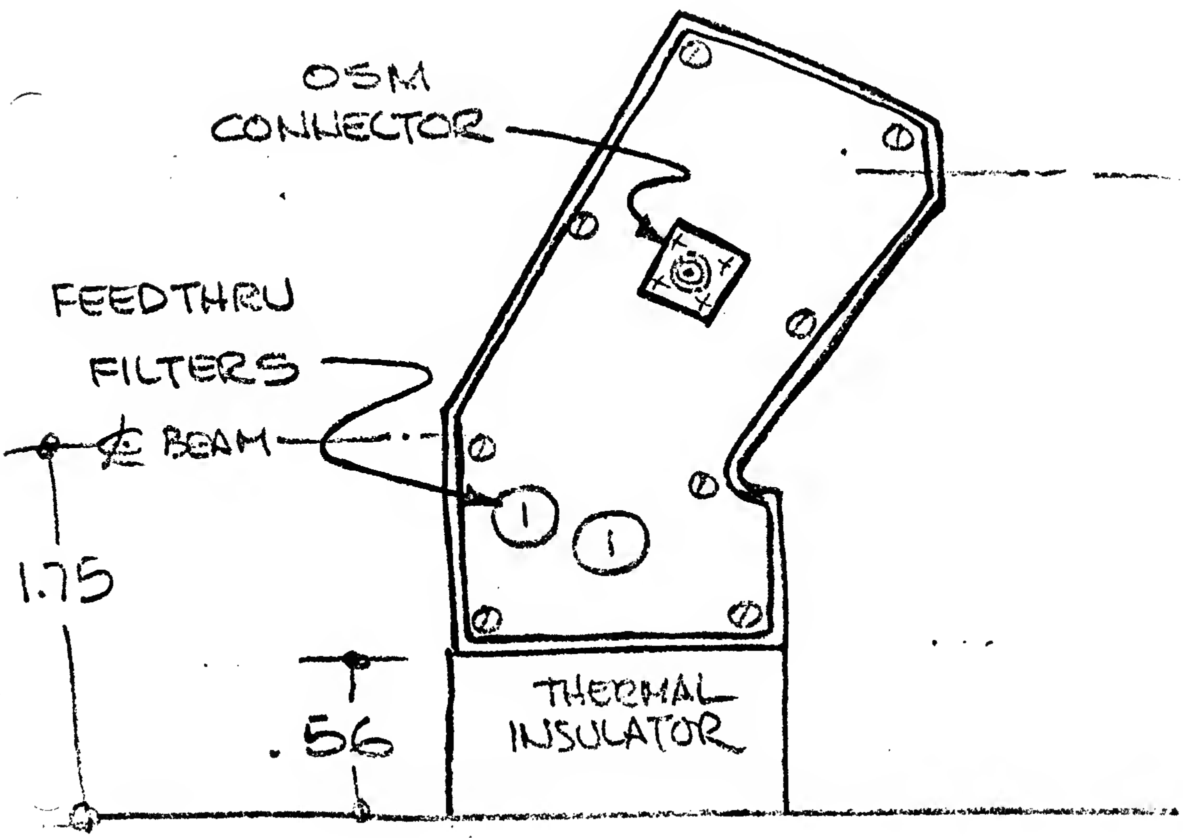

ALUM. ALLOY BASE PLATE
INVAR OPTICAL BASE PLATE
DETECTOR
MIRROR
COARSE POINTING MIRROR HOUSING
POWER SUPPLY
SYLVANIA LASER ELECTRONICS
SIGNAL PROCESSOR
LOCAL OSCILLATOR LASER
BACK UP LASER
MODULATOR
MODULATOR DRIVER
AEROJET-GENERAL CORPORATION
LCE BASE PLATE LAYOUT
70143
L-1236152

EXHIBIT C-4





SKETCH OF FTM MODULATOR SHOWING SPACE
REQUIREMENTS FOR OSM CONNECTORS

EXHIBIT C-5

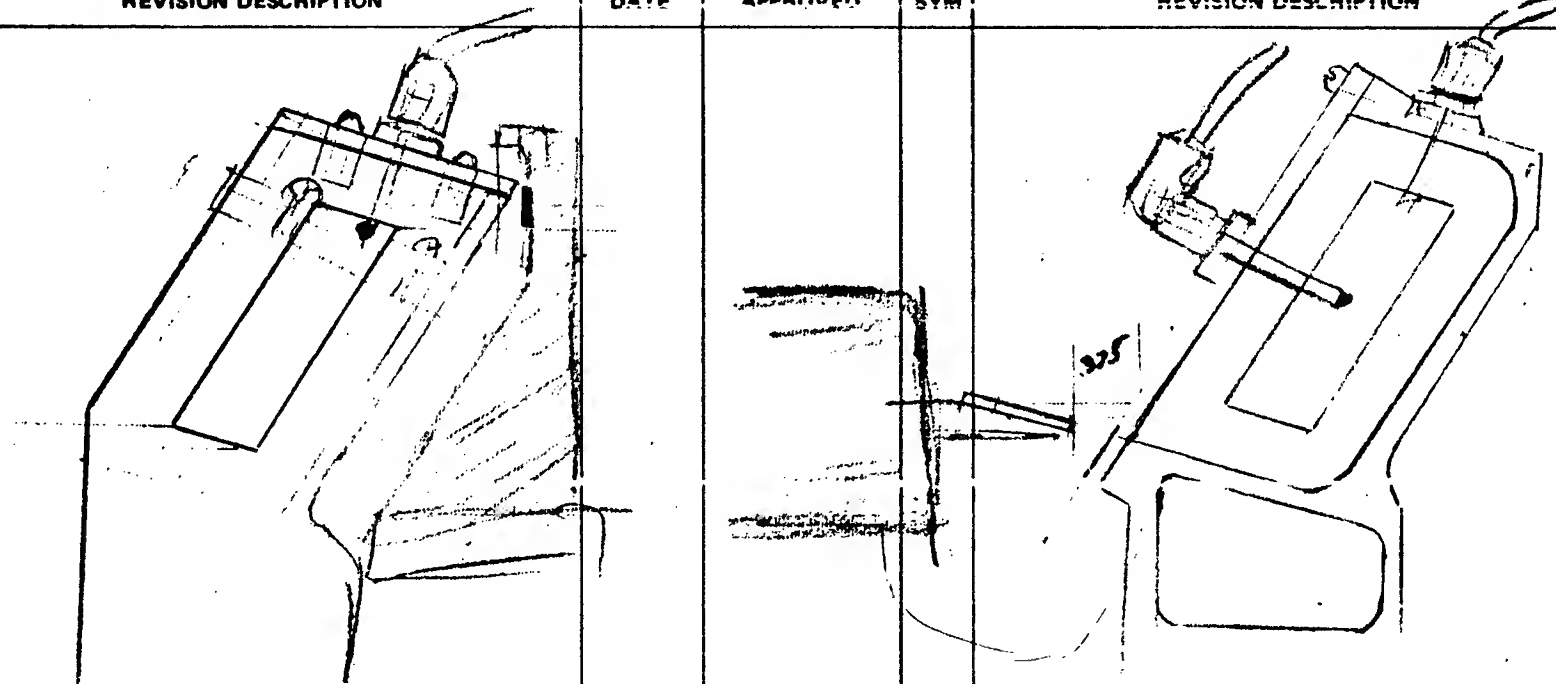
SYLVANIA ELECTRONIC SYSTEMS
DIVISION OF SYLVANIA ELECTRIC PRODUCTS INC.
MOUNTAIN VIEW, CALIFORNIA

PL

CODE IDENT 07397 | SHEET 1 OF | REV

PREP	DATE
CHK	
APPD	
APPD	

SYM	REVISION DESCRIPTION	DATE	APPROVED	SYM	REVISION DESCRIPTION	DATE	APPROVED



ECL 189C

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42

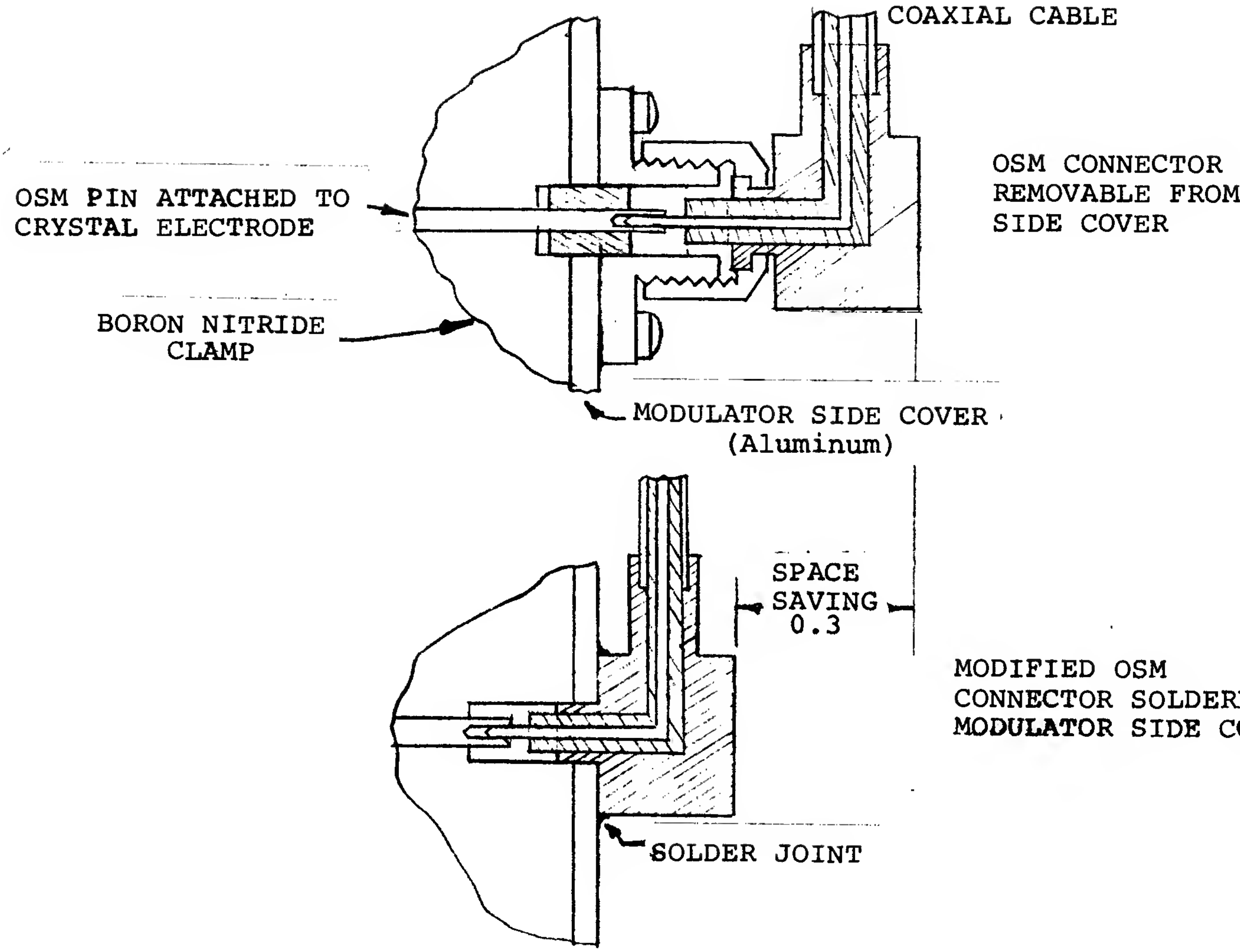
RECORD OF REVISION STATUS OF EACH SHEET

POSSIBLE CONNECTOR ARRANGEMENTS
EXHIBIT C-6

MODEL

PL

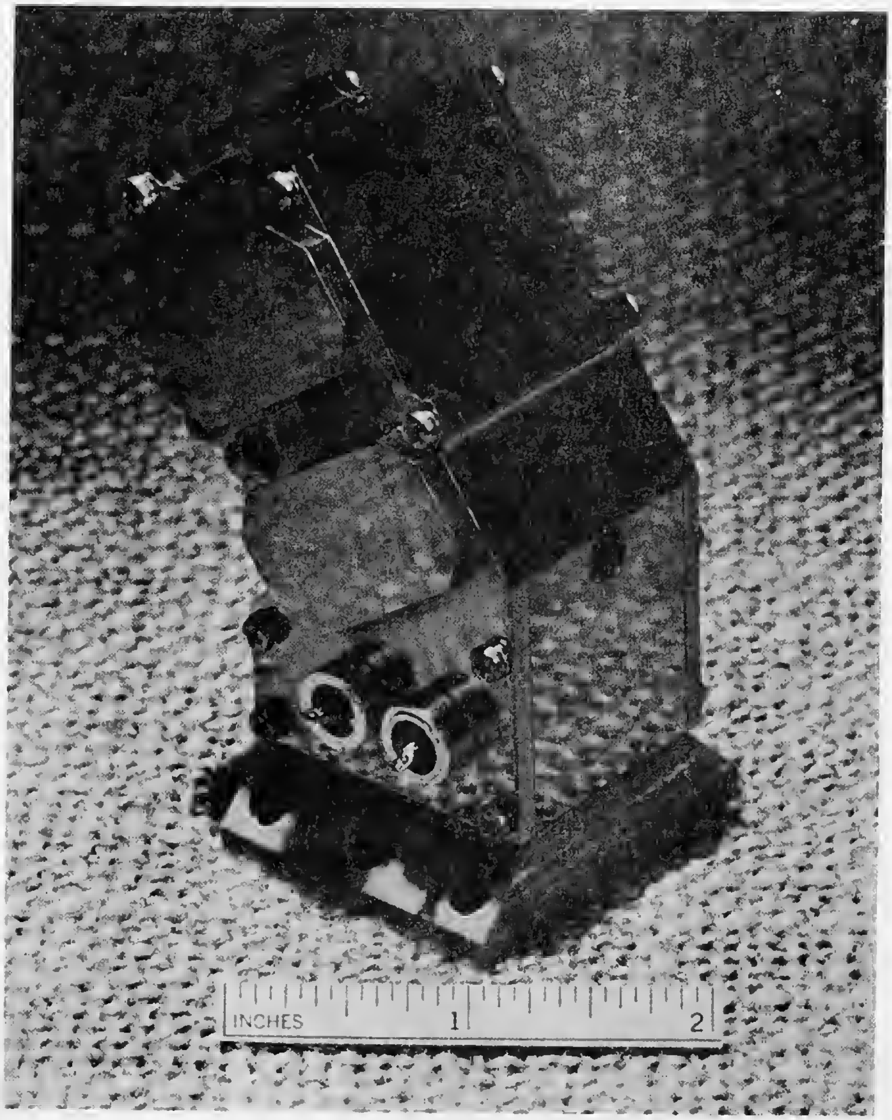
SES 1085.8 (6-68)



Coaxial cables are hard-wired to modulator when side covers are installed. Side cover is gold-plated to allow connector to be soldered with indium-gold eutectic solder.

TIM'S SOLUTION TO REDUCE THE WIDTH OF THE MODULATOR

EXHIBIT C-7



FINISHED MODULATOR FOR THE FUNCTIONAL TEST
MODEL OF THE LASER COMMUNICATION EXPERIMENT

EXHIBIT C-8

LASER HARDWARE (D)

Technical Problems

While working on the Laser Communications Experiment, Fred Moreno had to solve a number of technical problems. The solutions to these problems were undertaken as the need for the information arose. The following are statements by Fred of some of the technical problems he had to cope with. The problems are a distillation of his study of the situation.

Problem 1

One problem I had while working on the FTM was to determine the total input energy required to bring the modulator up to temperature from a cold start condition. During a cold start condition, the modulator began at the ambient temperature somewhere between 0 and 40°C. and was heated to operating temperature, about 68°C. As the modulator was heated, energy leaked off in the form of heat transfer. Thus the minimum energy required occurred if you could heat the modulator instantaneously, but this would require an infinite amount of power. A trade-off then existed. To minimize energy loss, a higher power input into the heater was required (until the modulator came up to temperature), but this in turn required the power supply to be larger to handle the greater load. I was to determine the variation in total energy as a function of available heater power and give this data to the spacecraft designers so that they could perform the trade-off study.

I first assumed that the power input to the heater would be a constant independent of time. This may or may not be true depending upon the power requirements of other parts of the space craft. I then assumed that I could treat the modulator as a one lump system with a known capacitance and resistance. I felt this assumption was a good one, inasmuch as the difference in thermal conductivity between the aluminum modulator housing and ceramic insulator was about 300 to 1. I assumed that the non-linear effects of radiation heat transfer were negligible, and the system was linear. Radiation accounts for less than 5% of the total heat transfer. Finally, I assumed no other heat input besides the heater.

The following data may be considered as given as part of the problem statement:

Thermal conductance (reciprocal of resistance)

$$\frac{KA}{L} = 0.051 \text{ Btu/hr.}^\circ\text{F.}$$

K = thermal conductivity
A = effective cross sectional area
L = length

Thermal capacitance

$$mc = 0.145$$

m = mass
c = specific heat

Temperature conditions: consider the time required to raise the temperature 100°F.

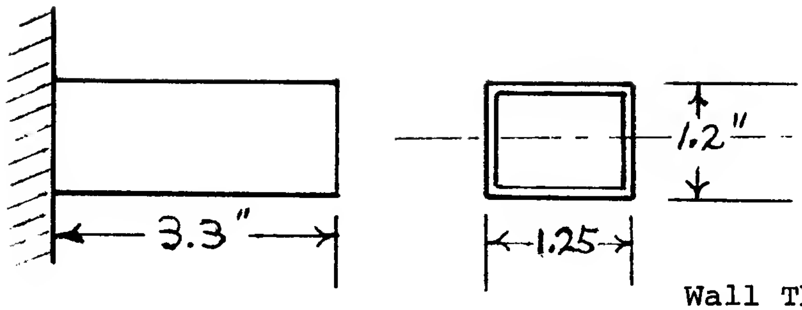
Power input: power available for heating could vary from 2 to 10 watts. Determine the time and energy required to raise the temperature 100°F. for a couple of power levels in this range.

Problem 2

As part of acceptance testing for the ATS equipment, the system would be run through vibration tests to simulate the launch environment. Vibration specifications were as follows:

Frequency Hz	*Input Level*
5 to 22	*0.5 in. double amplitude constant displacement*
22 to 200	*12.0 g (0 to peak)*
200 to 2000	*5.0 g (0 to peak)*

I ran a quick vibration analysis to see if the modulator would go through resonance during vibration, and if so, I wanted to make sure that the resonance was above 200 Hz so the stress levels would be the lowest possible. I assumed the modulator (Exhibit A-3 and Exhibit C-1) could be modeled as a simple cantilever beam with uniform cross section and uniform mass per unit length. These are poor approximations of the truth, but they allow a quick and dirty estimate of natural frequency.



Wall Thickness 0.1"
Wall Material: Aluminum, $E = 10^7$ psi
Total Weight: 0.7 lbs.

Problem 3

The thermal analysis of the modulator resulted in two coupled equations:

$$Q_{crystal\ dissipation} = K*(T_{mod}-T_{upper\ ambient})$$

$$Q_{heater} = K*(T_{mod}-T_{lower\ ambient})$$

At the time the analysis was performed, the crystal dissipation was not definitely established. Similarly, the heater power was not definitely known. However, some estimates could be made. The problem was to determine the modulator operating temperature and thermal conductance for the following data. The effects of thermal radiation are assumed to be negligible.

$$Q_{crystal} = Q_c = 0.78w$$

$$Q_{heater} = Q_h = 2.0w$$

$$T_{upper\ ambient} = T_{ua} = 40°C.$$

$$T_{lower\ ambient} = T_{la} = -5°C.$$

For parameter studies it was required to plot variations in modulator temperature as heater power is changed from 1.0 to 4.0 watts, with crystal dissipation held constant at 0.78 watts, and to plot variations in modulator temperature as the crystal dissipation is varied from 0.7 to 0.85 watts with the heater power held constant at 1.5 watts.

LASER HARDWARE (E)

Problem Solutions

Fred's solutions to the technical problems in Part D of the case are given here. These solutions are copied directly from his log book and are the solutions he used while designing the hardware for the Laser Communications Experiment.

Solution - PROBLEM 1

Note that total energy input is just power times the number of hours required to reach the desired temperature level.

<u>Transient Response - Heating</u>

MODEL

$$T = \frac{T - T_0}{T_{ss} - T_0}$$

T_0: base temp.

T_{ss}: Steady State Modulator Temp.

$$\boxed{m, c} \leftarrow q_i\text{, heater input}$$

$$\downarrow q_0 \qquad q_0 = \frac{KA}{L} T$$

Conservation of Energy $\quad q_i = mc \frac{dT}{d\Theta} + q_0 \qquad \Theta = \text{time}$

heat in, storage, loss

or $\quad mc \frac{dT}{d\Theta} + \frac{KA}{L} T = q_i$

rework $\quad \frac{dT}{d\Theta} = - \frac{KA}{Lmc} T + \frac{q_i}{mc}$

Integrating Factor $\quad e^{\int -\frac{KA}{Lmc} d\Theta} = e^{\frac{KA}{Lmc} \Theta}$

Multiply through by I. F.

$$\underbrace{e^{-\frac{KA}{Lmc}\Theta}\frac{dT}{d\Theta} + \frac{KA}{Lmc}T\,e^{-\frac{KA}{Lmc}\Theta}}_{\text{perfect differential}} = \frac{q_i}{mc}\,e^{-\frac{KA}{Lmc}\Theta}$$

or
$$\frac{d\left(Te^{-\frac{KA}{Lmc}\Theta}\right)}{d\Theta} = \frac{q_i}{mc}\,e^{-\frac{KA}{Lmc}\Theta}$$

separate, integrate

$$\int d\left(Te^{-\frac{KA}{Lmc}\Theta}\right) = \frac{q_i}{mc}\int_1^{\Theta} e^{-\frac{KA}{Lmc}\Theta}\,d\Theta$$

$$Te^{-\frac{KA}{Lmc}} = \frac{q_i}{mc}\left[-\frac{Lmc}{KA}\,e^{-\frac{KA}{Lmc}\Theta}\right|_0^{\Theta}$$

$$= \frac{q_iL}{KA}\left(-e^{-\frac{KA}{Lmc}} + 1\right)$$

or $\boxed{T = \frac{q_iL}{KA}\left(1-e^{-\frac{KA}{Lmc}\Theta}\right)}$ ← neglects radiation

Temp. response to heating

Initial temperature rise rate

$$\left.\frac{dT}{d\Theta}\right|_{\Theta = 0} = \frac{q_iL}{\cancel{KA}}\,\frac{\cancel{KA}}{Lmc}\left.e^{-\frac{KA}{Lmc}\Theta}\right|_{\Theta = 0}$$

$$= \underline{\frac{q_i}{mc}} \qquad \frac{\cancel{Btu}}{Hr.}\;\frac{°F}{\cancel{Btu}}$$

For the present case

$$q_i = 2W = 6.84 \text{ Btu/hr}$$

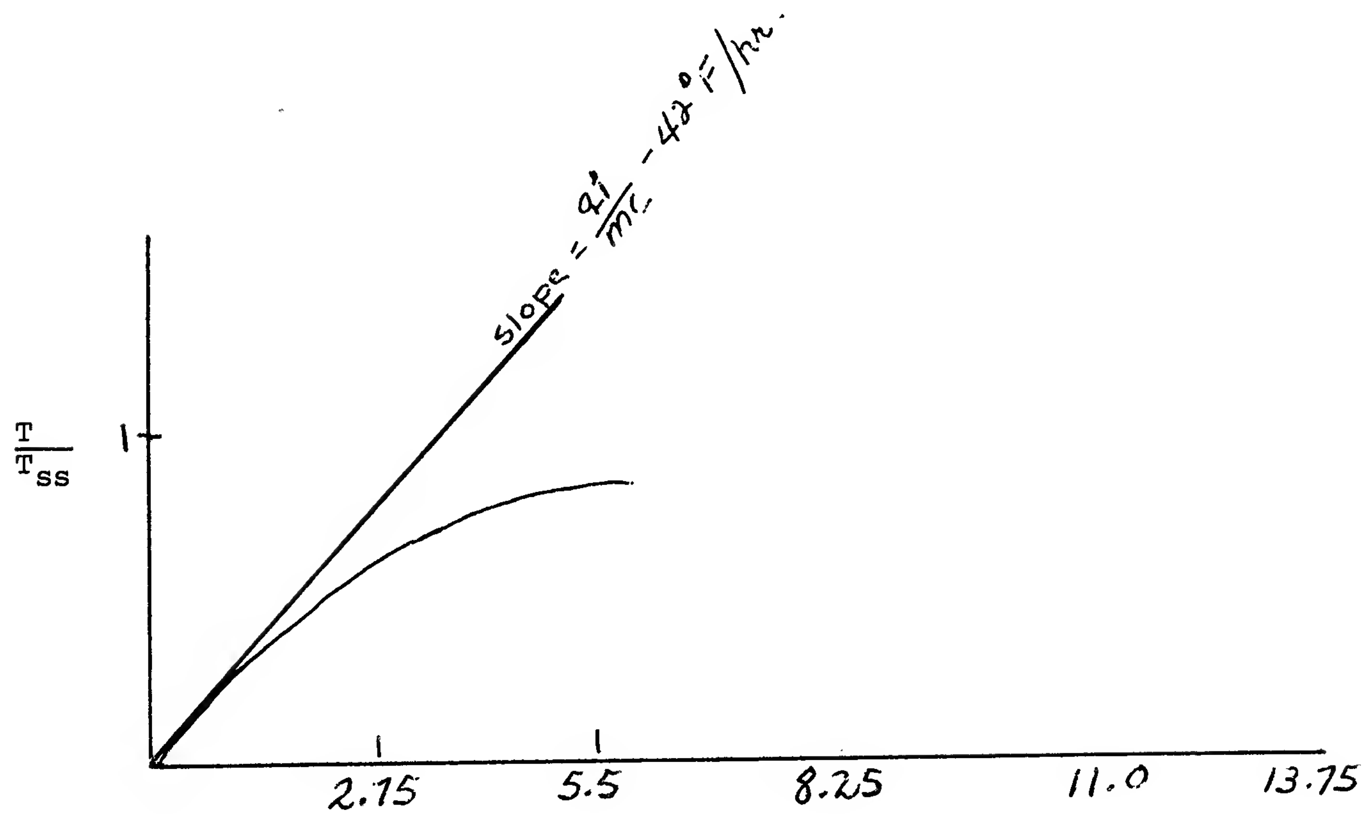
$$\frac{KA}{L} = .051 \text{ Btu/hr.°F}$$

$$\tau = 2.75 \text{ hrs.}$$

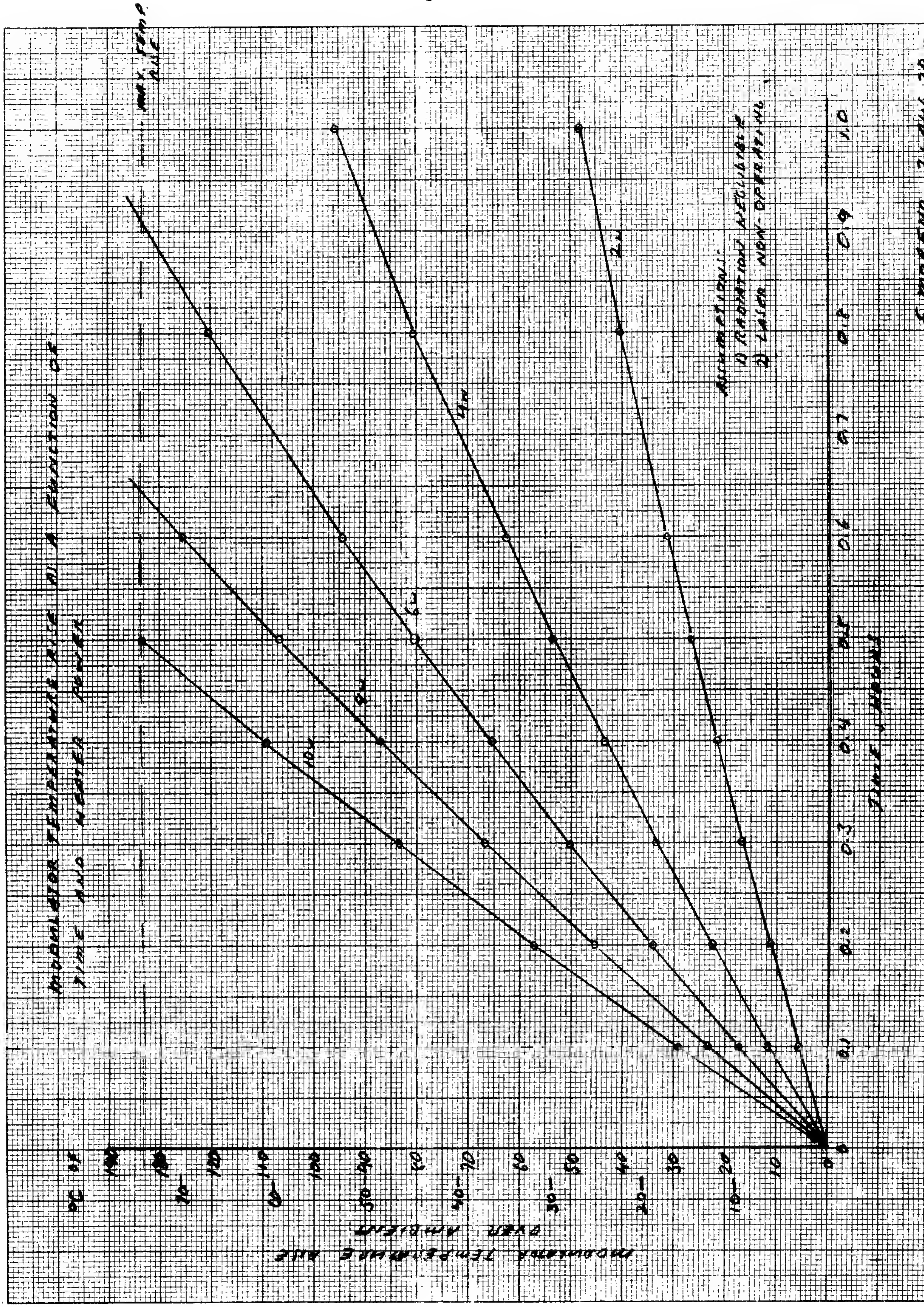
so

$$T = \frac{(6.84)}{.051} (1 - e^{2.75\theta})$$

$$= 134 \; (1-e^{-2.75\theta})$$



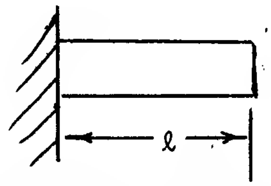
TIME, HOURS


MODULATOR TEMPERATURE RISE AS A FUNCTION OF
TIME AND HEATER POWER
°C °F
MAX. TEMP RISE
10w
8w
6w
4w
2w
MODULATOR TEMPERATURE RISE
OVER AMBIENT
TIME, HOURS
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
ASSUMPTIONS:
1) RADIATION NEGLIGIBLE
2) LASER NON-OPERATING
F MORENO 21 AUG. 78

Solution - PROBLEM 2

Natural Frequency of Modulator Structure

MODEL as simple cantilever beam



Natural Frequency $$\omega = \frac{3.52}{\ell^2} \left(\frac{EI}{m} \right) \text{rad/sec}^2$$

(from vibration handbook)

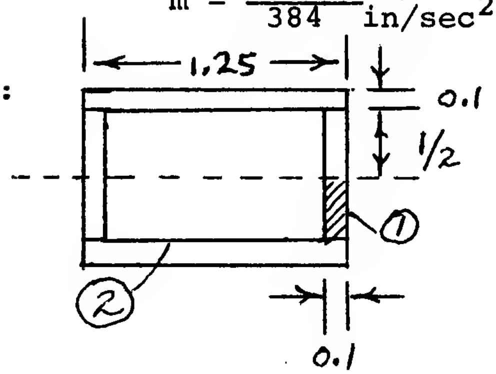
ℓ = beam length, in.
I = moment of inertia
E = Young's modulus
m = mass per unit length $\text{lb.sec}^2/\text{in}^2$

For present problem

$\ell = 3.30$ in.
$m = 0.7$ lbs/3.3 in. $= 0.212$ lb/in.

$$m = \frac{0.212 \text{ lb/in}}{384 \text{ in/sec}^2} = 5.5 \times 10^{-4} \text{ lb.sec}^2/\text{in}^2$$

I:



Rectangular Areas

1) $I = 1/12\ Bh^3 = (1/12)(1)(1.5)^3$
$= 1.04 \times 10^{-3} \text{ in}^4$

2) $I = I_0 + Ad^2$
$= (.125)(.55)^2$
$= .0375 = 3.75 \times 10^{-2} \text{ in}^4$

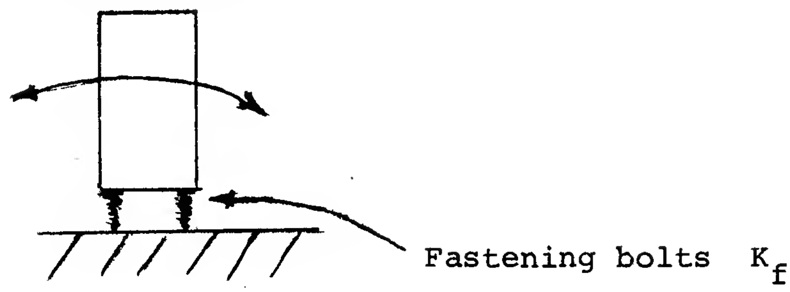
$$I \text{ total} = 2(3.75 \times 10^{-2}) + 4(1.04 \times 10^{-3})$$
$$= 7.5 \times 10^{-2} + 4.16 \times 10^{-3}$$
$$= 7.9 \times 10^{-2} \text{ in}^4$$

so

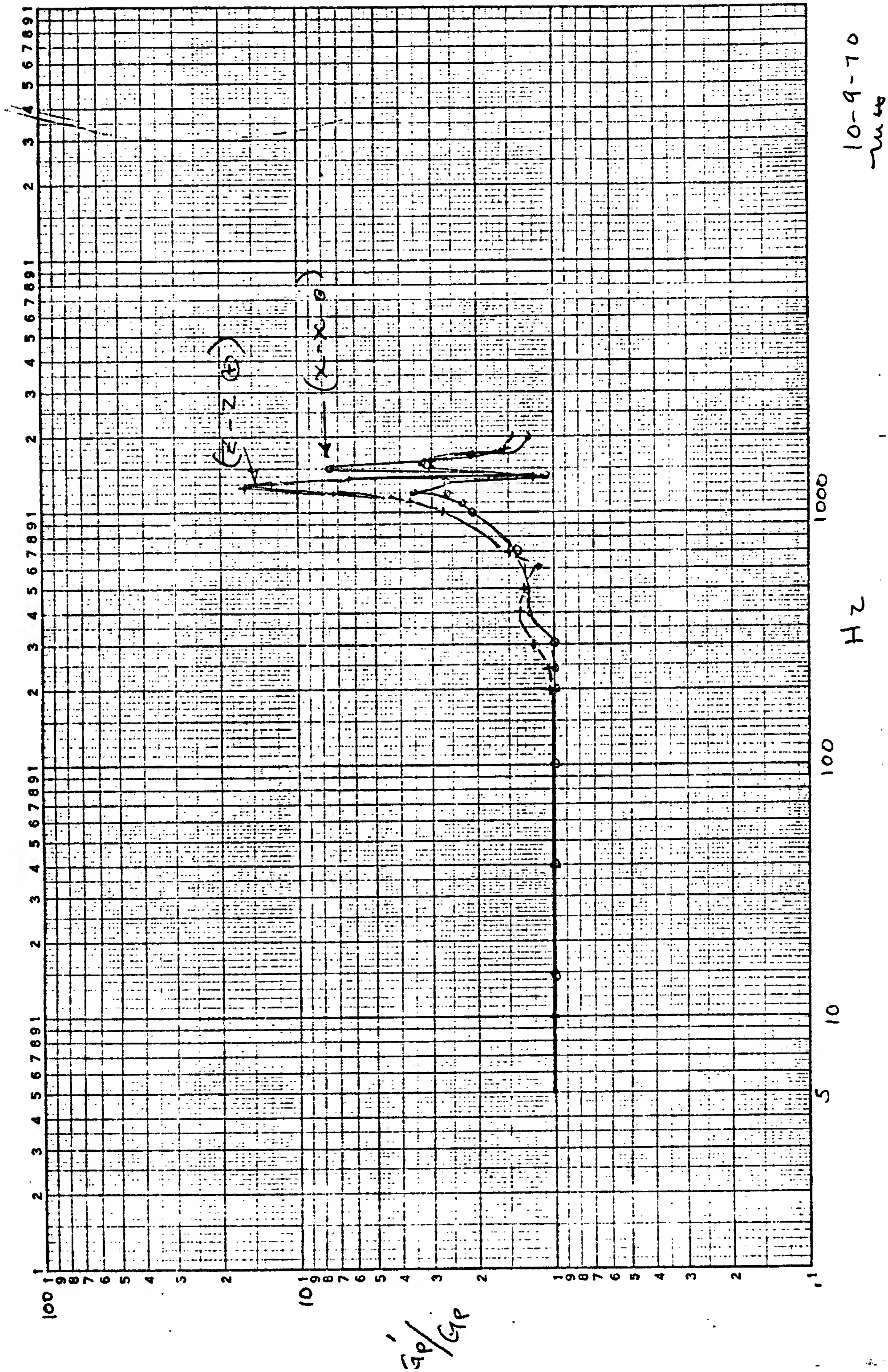
$$\omega = \frac{3.52}{(3.3)^2} \left[\frac{(10 \times 10^6)(7.9 \times 10^{-2})}{(5.5 \times 10^{-4})} \right]^{1/2}$$

$$= 1.22 \times 10^4 \text{ rad/ sec}$$ $\underline{\omega = 1.9 \times 10^3 \text{ cps}}$

Note: Neglected effect of fasteners. Will lower frequency.



This is the result of the analysis. The next page gives a plot of the vibration test to show resonance. The tests and analysis are clearly not in complete agreement. Why?



RESONANCE SURVEY

Solution - PROBLEM 3

Solve for K^*

$$K^* = \frac{Q_c}{(T_m - T_{ua})} \qquad \frac{W}{°C}$$

Substitute

$$\frac{Q_c\ (T_m - T_{la})}{(T_m - T_{ua})} = Q_h$$

$$Q_c T_m - Q_c T_{la} = Q_h T_m - Q_h T_{ua}$$

$$T_m (Q_c - Q_h) = Q_c T_{la} - Q_h T_{ua}$$

or

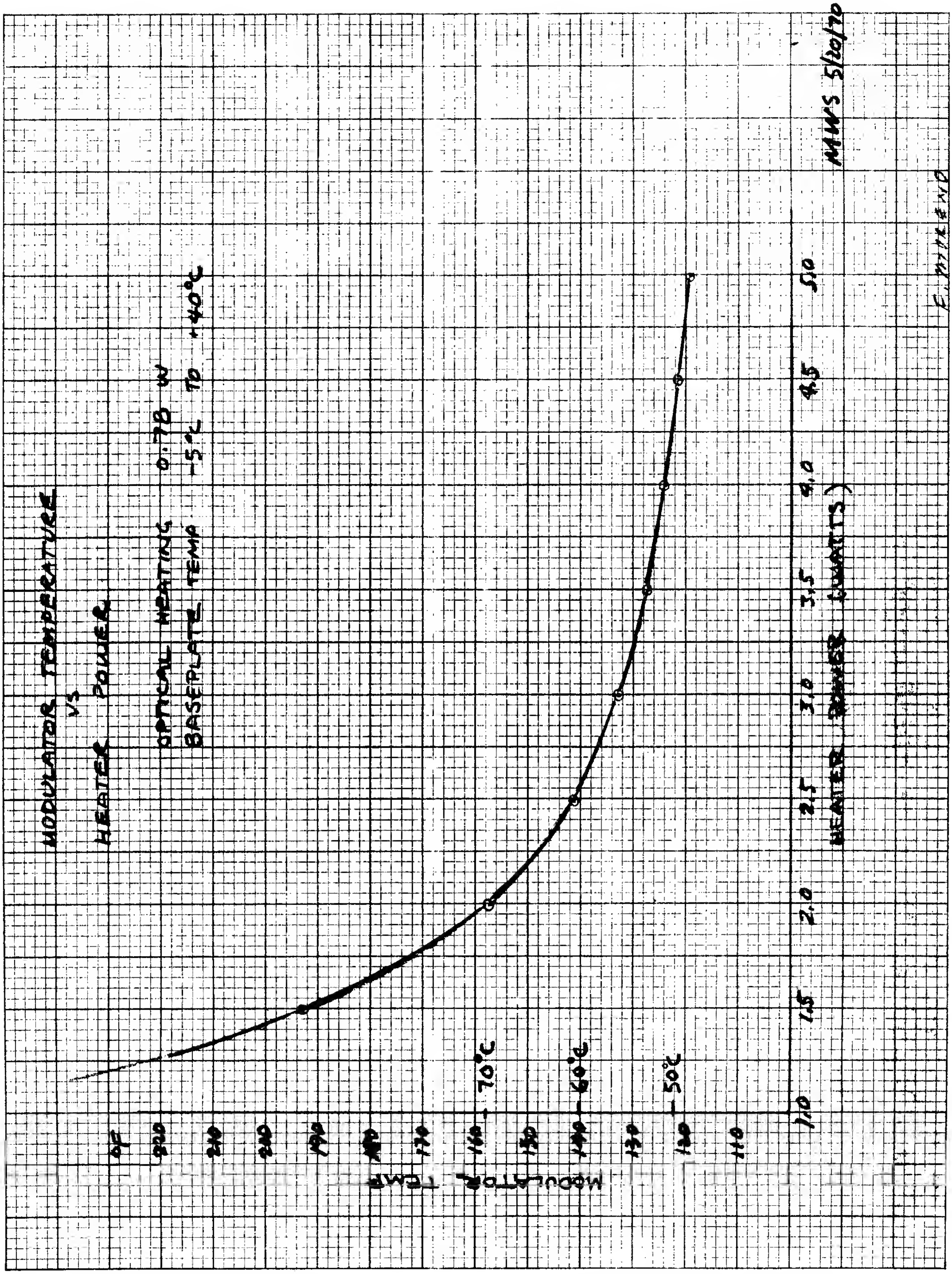
$$T_m = \frac{Q_h T_{ua} - Q_c T_{la}}{Q_h - Q_c}$$

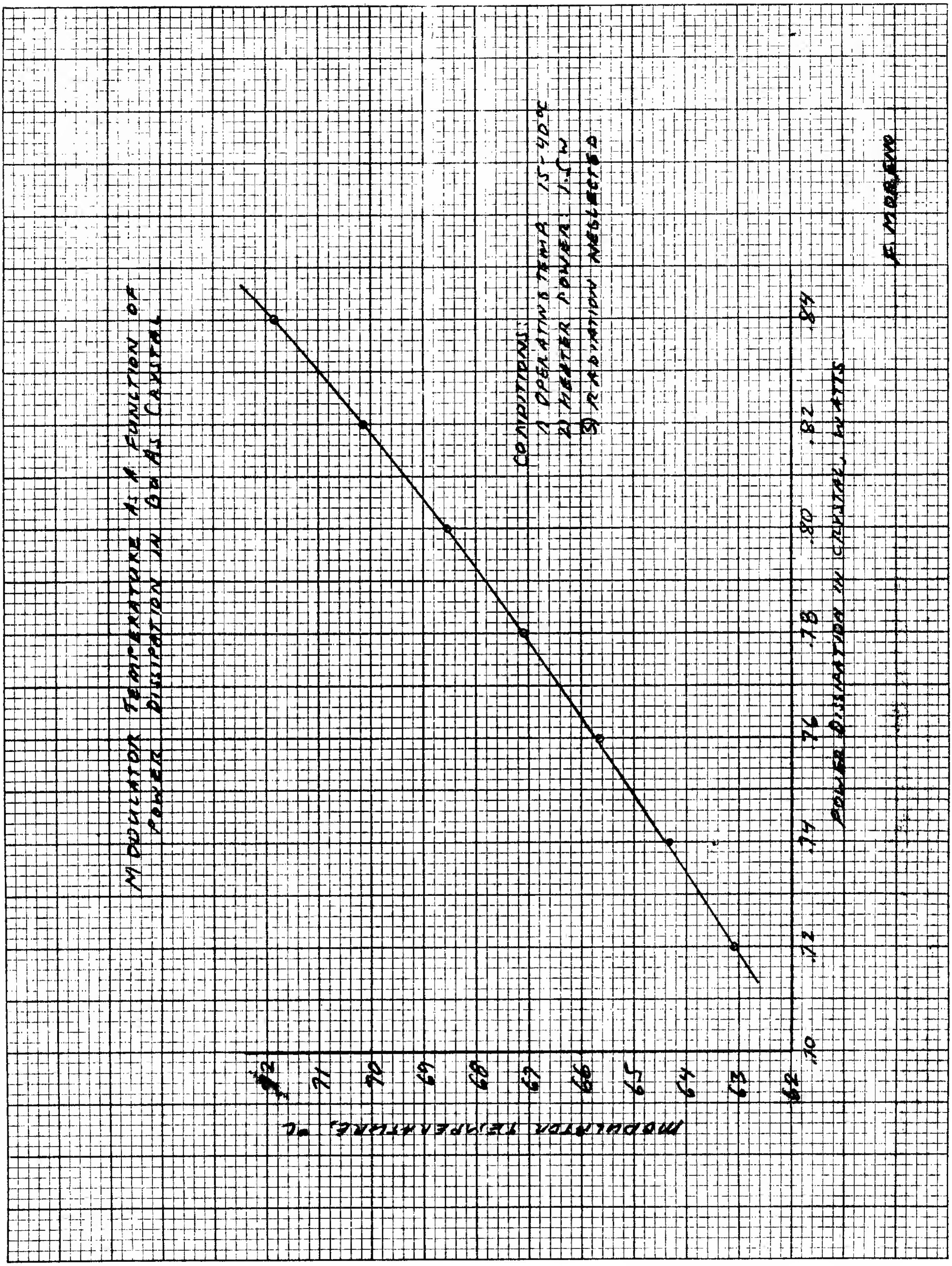
Substitute values

$$T_m = 68.77°C$$

$$1/K = 36.88°C/W$$

Plots from parameter study are shown on following pages.


MODULATOR TEMPERATURE
VS
HEATER POWER
OPTICAL HEATING 0.78 W
BASEPLATE TEMP -5°C TO +40°C
MODULATOR TEMP
°F
220
210
200
190
180
170
160
150
140
130
120
110
70°C
60°C
50°C
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
HEATER POWER (WATTS)
MWS 5/20/70


MODULATOR TEMPERATURE AS A FUNCTION OF POWER DISSIPATION IN GaAs CRYSTAL
CONDITIONS:
1) OPERATING TEMP. 15-40°C
2) HEATER POWER 1.5W
3) RADIATION NEGLECTED
.70 .72 .74 .76 .78 .80 .82 .84
POWER DISSIPATION IN CRYSTAL, WATTS
62 63 64 65 66 67 68 69 70 71 72
MODULATOR TEMPERATURE, °C